The Effects of Temperature, Sleep Restriction, and Physical Activity on the Sleep Architecture and Cognitive Performance of Volunteer Firefighters During Various Simulated Wildland Fireground Tours

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A thesis submitted in fulfilment of the requirement for the degree of Doctor of Philosophy

Appleton Institute
Central Queensland University
April, 2018

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Acknowledgments

I would sincerely like to thank the following people for making this PhD possible:

My supervisors Professor Sally Ferguson and Dr Bradley Smith, without your guidance, continual feedback and assistance this PhD would not have been possible. A special thanks to Sal for allowing me the opportunity to complete a PhD in the first place.

I would also like to thank my co-authors for their important contributions including Dr Sarah Jay, Dr Grace Vincent, and Dr Jill Dorrian. A very special mention and thank you to Jill for her ingenious help with figuring out the statistics.

Out of everyone I would like to thank my parents Kym and Phil Cvirn for their continuous support over the years. Without their help and support I would never have had the liberty and opportunity to successfully pursue my own interests. Also a special mention to my nanna Mary, for never forgetting to send me a birthday present every year, bless her soul. It's okay now nan, you can stop sending me the presents and let me start sending them to you! Also to my main man Nick Bettison, for being a true best friend and understanding all the times I haven't been there simply because I was working on this! This thesis is also dedicated to the everlasting memory of Nanna Elsie, Poppy, and also Pa Victor, bless their souls in heaven.

One may ask where too from here?

Well at the very beginning of my PhD, Sal, in supervisory mode sat me down and asked
"What is your research question going to be Michael?"
"I want to study dreams!" I replied.
"How would you study that scientifically?" she asked.
Somewhat befuddled I stared blankly at the wall as if expecting an answer, or an idea to pop into my mind. Although, it never came!
However, as fate would have it whilst completing the final edits to this thesis it would be revealed that in 1957 William Dement and Nathaniel Kleitman published a paper in the Journal of Experimental Psychology titled "The relation of eye movements during sleep to dream activity: An objective method for the study of dreaming."

At present, I am intrigued by this study from the past! So what future research holds could be very interesting indeed.

As this thesis fulfils the requirement for a doctorate in philosophy, with philosophy taking the literal meaning from the Greek translation 'love of wisdom', it is only fair then, that it should too also include some notions pertaining to the state of reality or existence. After all philosophy is the study of the fundamental nature of knowledge, reality, and existence, especially when considered as an academic discipline.

> "The day science begins to study non-physical phenomena, it will make more progress in one decade than in all the previous centuries of its existence." - Nikola Tesla

> "This paper argues that *at least one* of the following propositions is true: (1) the human species is very likely to go extinct before reaching a "posthuman" stage; (2) any posthuman civilisation is extremely unlikely to run a significant number of simulations of their evolutionary history (or variations thereof); (3) we are almost certainly living in a computer simulation. It follows that the belief that there is a significant chance that we will one day become posthumans who run ancestor-simulations is false, unless we are currently living in a simulation. A number of other consequences of this result are also discussed (p. 242)." - Professor Nick Bostrom, Oxford University, Faculty of Philosophy

> "There's a one in billions chance we're in base reality." - Elon Musk

Acknowledgement of Support Provided by the Australian Government

This research higher degree candidature was supported by a Scholarship from the Australian Government's Research Training Program / Research Training Scheme. I gratefully acknowledge the financial support provided by the Australian Government.

Acknowledgement of Financial Support

I gratefully acknowledge the funding received from the Bushfire and Natural Hazard Cooperative Research Centre which has supported this research.

Declaration of Authorship and Originality

I, the undersigned author, declare that all of the research and discussion presented in this thesis is original work performed by the author. No content of this thesis has been submitted or considered either in whole or in part, at any tertiary institute or university for a degree or any other category of award. I also declare that any material presented in this thesis performed by another person or institute has been referenced and listed in the reference section.

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Overview

To date, investigations relating to the effects of stressors such as sleep loss, ambient temperature, physical activity and hydration on sleep architecture and cognitive performance- either individually or in combination- are relatively scarce. What is known has almost entirely come from single-disciplinary approaches including sport or exercise research conducted in the laboratory, or military combat scenarios conducted in the field. These are extreme contexts which 1. Have little external validity (i.e., do not represent realistic situations, or participants); 2. Often avoid assessing the impact of external stressors in combination; 3. The stressors used are often extreme. There is a particular need to determine the impact of external stressors on the sleep and cognition of those who engage in physically demanding occupations. One such example is the role of an Australian volunteer wildland firefighter - who undertakes physically demanding work, in extreme conditions over multiple days.

In Australia, where wildfires are common, volunteer wildland firefighters are critical for protecting regional and remote communities across Australia. They are frequently called upon (particularly in the summer months) at short notice, to perform physical manual-handling activity in hot temperatures (typically between 30-40 degrees), at any time of the day or night, and for multiple days. Heat-related illness including severe dehydration from hot temperatures and inadequate fluid intake are common, and the potential for fatigue-related accidents resulting from sleep loss, heat, and physical work, pose a significant risk to health and safety while undertaking these tasks. Knowledge about the effects of multiple work-place stressors such as sleep loss, physical activity, ambient temperatures and/or dehydration in combination with normal control conditions is critical for better informing wildland fire agencies in predicting the efficacy of workplace personnel under such conditions. For example, this information could be used to provide safeguards for managing risks associated with sleep loss, physical activity, ambient temperature and dehydration.

The purpose of this thesis was twofold:

- to assess the effects on sleep physiology (quantity and quality) of physical activity, warm or 'hot' and thermoneutral or 'cool' ambient temperatures (Chapter 4) and sleep loss (Chapter 5)

- to investigate the effects on mental functions as assessed by cognitive performance, of physical activity, hot and thermoneutral temperatures and dehydration (Chapter 6) and the combination of the effects of physical activity, temperature and sleep restriction (Chapter 7).

Ideally, these stressors would either be explored in the field, or in strict laboratory conditions. However, both remain challenging. During wildfires, natural fluctuations in temperature, variability of intensity, direction of the fire, and changes in wind speed and humidity all represent uncontrollable variables. Further, the expertise, time and equipment required to collect all relevant data in the field is prohibitively expensive. Attempting to measure sleep and cognitive performance variables while capturing environmental data may also have the potential to impact on firefighting operations. With this in mind, this thesis presents a novel body of research using a high-fidelity work simulation that is based on real life wildfires, and uses active volunteer firefighters. This allowed the ability to assess changes in sleep physiology and cognitive performance in response to multiple stressors with direct relevance to industry. However, the studies presented in this thesis are still simulations of wildfire suppression where in comparison to real life situations physical activity requirements, temperature, and sleep restriction may vary.

The thesis is split into four studies. Study 1 (Chapter 4) shows the effects of cool and warm temperatures on the sleep physiology of wildland firefighters over four nights of simulated wildland firefighter suppression, reflecting natural variations in temperature firefighters' face during working conditions. Study 2 (Chapter 5) demonstrates the effects on firefighters' sleep physiology of both cool and warm temperatures during a four-night simulated wildfire suppression with two nights of sleep restriction. Study 3 (Chapter 6) then shows the effect on firefighters' cognitive performance from both cool and warm temperatures with wildland firefighter physical tasks and resulting hydration levels over the course of a 12 h simulated wildfire suppression work shift. Finally, Study 4 (Chapter 7) demonstrates the effects on firefighters' cognitive performance of cool and warm temperatures, with the addition of physical activity and two nights of sleep restriction over three days of simulated wildfire suppression. Collectively, the results of this thesis demonstrate a novel contribution to the understanding of the interrelationship between night-time sleep physiology and daytime cognitive performance by providing insight into the effects of temperature, sleep loss and concomitant physical activity, testing, single, dual, and tri-stressors.

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List of Abbreviations

α	alpha
AASM	American Academy of Sleep Medicine
ACT	Australian Capital Territory
ANOVA	Analysis of variance
AEE	activity energy expenditure
am	ante meridiem
AUD	Australian dollars
β	Beta
B_m	body mass
BMI	body mass index
B_w	body weight
CBT	core body temperature
CFA	country fire authority
CFS	country fire service
cm	centimetre
Co.,	company
CPT	continuous performance test
CQU	Central Queensland University
CRT	choice reaction time
°C	degrees Celsius
DVs	dependent variables
EEG	electroencephalogram
EMG	electromyogram
EOG	electro-oculogram
f	females
g	gram(s)
GHQ	General Health Questionnaire
$g \cdot mL^{-1}$	grams per milliliter
h	hours
Hz	hertz
ID	identification

Inc.,	incorporated
ISO	international organisation for standardisation
kg	kilograms
L	litres
LED	light-emitting diode
LOC	left outer canthus
LSD	least significant differences
min	minute(s)
min^{-1}	per minute
ml	millilitre(s)
ms	milliseconds
m	males
n	number
NSW	New South Wales
NREM	non rapid eye movement
OR	oregon
PAR	physical activity ratio
PDA	personal digital assistant
pm	post meridiem
PPC	personal protective clothing
PPE	personal protective equipment
PSG	polysomnography
PVT	psychomotor vigilance task
®	registered
REM	rapid eye movement
RH	relative humidity
ROC	right outer canthus
RT	reaction time
RRT	reciprocal reaction time
SART	Sustained Attention to Response Task
SCBA	self-contained breathing apparatus
SCN	suprachiasmatic nucleus
SD	standard deviation
SE	standard error

sec	second
SEM	standard error of the mean
SOL	sleep onset latency
SPSS	statistical package for the social science
SUSOPS	sustained military operations
SWA	slow-wave activity
SWS	slow-wave sleep
T_{db}	dry bulb temperature
TIB	time in bed
™	trademarked
TSD	total sleep deprivation
TST	total sleep time
U_{sg}	urine specific gravity
VO_{2max}	maximal oxygen consumption
WASO	wake after sleep onset
~	approximately
>	greater than
≥	greater than or equal too
<	less than
≤	less than or equal too
=	equal(s)
%	percentage
”	inch(es)

List of Publications and Conference Presentations

Cvirn M., Smith, B. P., Jay, S. M., & Ferguson, S. A. (2014). What happens to the sleep of volunteer firefighters during exposure to hot temperatures and restricted sleep during a wildland fireground tour? *Adelaide Sleep Retreat Program Guide and Abstract Book, 5th annual meeting*

Cvirn M., Smith, B. P., Jay, S. M., & Ferguson, S. A. (2014). Sleep characteristics of volunteer firefighters exposed to different temperatures during a wildland fireground tour simulation. *The Time of Your Life. Australasian Chronobiology Society, 11, p.21*

Cvirn, M. A., Dorrian, J., Smith, B. P., Jay, S. M., Vincent, G. E., & Ferguson, S. A. (2017). The sleep architecture of Australian volunteer firefighters during a multi-day simulated wildfire suppression: Impact of sleep restriction and temperature. *Accident Analysis & Prevention, 99*, 389-394. doi: https://doi.org/10.1016/j.aap.2015.11.013

Cvirn, M. A., Smith, B. P., Jay, S. M., Vincent, G., & Ferguson, S. A. (2015). The impact of temperature on the sleep characteristics of volunteer firefighters during a wildland fireground tour simulation. In: Kennedy, G., & Sargent, C. (Eds). *The Time of Your Life. Australasian Chronobiology Society, Melbourne, Australia*, pp. 18-24.

Papers contributed to during candidature, but not included in this thesis include:

1. Christoforou T, Cvirn M, Ferguson SA, Armstrong TA, Smith B. (2013). The effect of sleep restriction and exposure to physical activity on the cognitive ability of volunteer firefighters across a 3-day simulated fire-ground tour. In: Sargent C, Zhou X (Eds). Sleep, performance and well-being in adults and adolescences. Australasian Chronobiology Society, Adelaide, Australia, pp. 13-17.
2. Armstrong TA, Cvirn M, Ferguson SA, Christoforou T, Smith B. (2013). Can Australian bush fire fighters accurately self-monitor their cognitive performance during a 3-day simulated fire-ground campaign. In: Sargent C, Zhou X (Eds). Sleep, performance and well-being in adults and adolescences. Australasian Chronobiology Society, Adelaide, Australia, pp. 18-23.

Chapter 1: Introduction

1.1 Background

Wildfires, synonymous with wildland fires or known as bushfires in Australia, can be defined as any non-structural unrestrained fire typically occurring from the combustion of natural fuels such as grass, scrub, bush, vegetation or shrubs, in locations where human development is not substantial; such as farmland; rural communities or national parks (Everett, Kocienski, & Lobel, 2012; NWCG, 2014). Wildland fires present an annual threat to communities around the world, particularly Australia, North America, South America and Southern Europe (Hyde et al., 2007; San-Miguel-Ayanz et al., 2016; Teague, McLeod, & Pascoe, 2009). All of these countries have endured disastrous wildland fires with the frequency, duration and severity forecast to increase with a climactic global trend towards warmer, less humid summers (Kloster & Lasslop, 2017). Globally, wildland fires claim hundreds of lives and cost billions of dollars in suppression and recovery each year (Hyde et al., 2007), destroying homes, land, livestock and crippling communities (Liu, Stanturf, & Goodrick, 2010). The trend toward more frequent and more severe fire events is also placing an increasing strain on the demand and service of firefighters (Raines et al., 2012).

Australia is considered one of the most bushfire prone countries in the world, showing an unprecedented increase in wildfires over the last 10 years (Aisbett, Wolkow, Sprajcer, & Ferguson, 2012) and an average yearly expenditure on wildfire fighting that exceeds 70 million dollars (AUD; McLennan & Birch, 2005). Annually, over 200,000 Australian volunteers from fire and rescue emergency services face exposure to hazardous occupational and environmental stressors whilst carrying out their duties in the field (Aisbett et al., 2012).

Multi-day fire deployments require wildland firefighters to perform extended, 12 h to 15 h shifts, both day- and night-time, for three to five consecutive days, with little rest between shifts (Aisbett et al., 2012; Cater et al., 2007; Phillips, Raines, Nichols, & Aisbett, 2007). The shortened rest periods between work shifts results in varying amounts of sleep loss being reported by Australian firefighters during multi-day wildfire campaigns (Cater et al., 2007). Sleep loss across multiple nights has been shown to lead to a decline in cognitive function (Van Dongen, Maislin, Mullington, & Dinges, 2003), also influencing the subsequent nights' sleeping patterns (Belenky et al., 2003).

Wildland fires are also known for their hot, dry, and windy environmental conditions with temperatures typically ranging between 35-45°C (Cheney, 1976). For example, the catastrophic February 2009 Black Saturday bushfires in Victoria, Australia, that resulted in 173 fatalities, were associated with temperatures as high as 46.4°C (Teague, McLeod, & Pascoe, 2010). Wildland firefighters are also required to perform prolonged periods of low-intense physical labour interspersed with bouts of moderately high intense activity (Cuddy, Gaskill, Sharkey, Harger, & Ruby, 2007; Phillips et al., 2012; Raines et al., 2013; Rodriguez-Marroyo et al., 2012). In order to shield the firefighter from environmental hazards, personal protective clothing is required. The clothing is thick, heavy, with impermeable layers, and includes a helmet which encapsulates the head, thereby increasing body heat retention (Barr, Gregson, & Reilly, 2010). The limited water-vapour permeability of the personal protective clothing layers limits the rate of evaporative cooling, thereby increasing the rate of dehydration (Barr et al., 2010). Australian wildland firefighters have been shown to arrive on shift dehydrated and, when working in hot conditions (37°C), remain dehydrated throughout the entire shift (Raines, Snow, Nichols, & Aisbett, 2015). The cumulative effect of physically demanding tasks, exposure to ambient heat, body heat retention and dehydration increase thermoregulatory strain. Thermoregulatory strain is in turn associated with declines in cognitive capacity, exhaustion, confusion, disorientation, loss of consciousness, heart attacks and in extreme cases death (Barr et al., 2010). From a review of five to 10 year injury statistics from south-eastern Australian fire agencies, heat related injuries were found to be the third highest leading cause of all fireground related injuries (Aisbett, Phillips, Sargeant, Gilbert, & Nichols, 2007).

Despite the clear risks to health, well-being and operational performance, research investigating the interplay between sleep, ambient temperature, physical work, dehydration and cognitive performance does not exist for the wildland firefighting population. Since there are a number of adverse outcomes related to sleep loss, heat, and dehydration, the potential influence of these occupational and environmental stressors on sleep patterns and cognitive performance should be an ongoing research priority to assist in the vital role firefighters perform in protecting public safety.

1.2 Research problem

In the field firefighters are known to undergo varying of amounts of sleep loss throughout wildfire suppression (Cater et al., 2007; Gaskill & Ruby, 2004). More recently, objective measurements of firefighters sleep using activity monitors showed a substantial reduction in the amount of sleep obtained during work periods compared to rest days (Vincent, Aisbett, Hall, & Ferguson, 2016). While polysomnography and electroencephalographic measures have previously been employed in field based studies such as sustained military operations (SUSOPS; Haslam, 1982), presently no research exists objectively measuring the sleep patterns of wildland firefighters either in the field, during simulations, or in the laboratory. Furthermore, there is currently no available laboratory research examining the effects of combining stressors such as temperature, sleep restriction and physical activity, on sleep architecture in any population. Laboratory research has shown adverse effects on sleep associated with:

- single stressors: sleep restriction (Belenky et al., 2003; Van Dongen, Maislin, et al., 2003), physical activity (Horne & Staff, 1983), hot temperatures (Haskell, Palca, Walker, Berger, & Heller, 1981), and cool temperatures (Muzet, Libert, & Candas, 1984);
- double stressors: hot temperatures and sleep restriction (Bach et al., 1994);
- triple stressors: only in military designed studies (Haslam, 1982).

In sum, the available literature on firefighters' sleep is limited to self-reports and activity monitor measurements. Further, information on sleep and sleep architecture comes from military operation simulations or combinations of stressors under highly controlled and artificial laboratory conditions that do not reflect wildfire suppression scenarios. For e.g., military studies typically include periods of total sleep loss for one to three days, that does not reflect typical sleep loss in firefighters, which is more gradual and occurs over a period of nights (Haslam, 1984; Vincent et al., 2016). It follows then that fire agencies would benefit from an assessment of firefighters' sleep architecture during conditions that more accurately reflect those experienced during wildfire suppression operations.

As highlighted earlier, wildfires are predicted to increase in frequency and burn for longer periods of time (Liu et al., 2010), placing an additional strain on firefighters' health and

safety. There remains however, a lack of research examining the types of heat stress and exertion experienced by fire personnel performing extended duration, manual-handling fire suppression activities in a range of temperatures. Presently there is no available literature on the effects of ambient temperature on wildland firefighter hydration and cognitive performance. Research from laboratory based studies has shown impaired cognitive performance with dehydration induced in the heat (Cian, Barraud, Melin, & Raphel, 2001) dehydration induced by physical activity (Cian et al., 2000) or dehydration induced by heat and physical activity in combination (Gopinathan, Pichan, & Sharma, 1988; Sharma, Pichan, & Panwar, 1983). However, these studies have only examined the effect of ambient temperature and dehydration over one exercise/heat session (Cian et al., 2000) or have employed physical activity protocols (for e.g., treadmill exercise; Cian et al., 2001) that do not reflect the types of activities, or work-to-rest ratios seen in wildfire suppression operations (Phillips et al., 2012; Phillips et al., 2011). Fire agencies would benefit from data on the hydration status and cognitive functioning of personnel during fire suppression shifts as they impact on the overall success of the fire suppression task. Hence, research quantifying the effect of hydration on the cognitive performance of firefighters performing fire suppression tasks in the heat and also in cooler temperatures is required.

Firefighting is a demanding occupation and establishing the association between sleep obtained between successive shifts is critical for fire agencies in implementing workplace fatigue management strategies during multiple days of wildfire suppression. Despite this, there is currently no research examining firefighters' cognitive performance during sleep restriction with varying ambient temperature in wildfire suppression conditions. Presently, there are few studies that examine the cognitive performance of firefighters in the heat (Smith, Manning, & Petruzzello, 2001; Smith & Petruzzello, 1998; Smith, Petruzzello, Chludzinski, Reed, & Woods, 2001) and these used structural fire simulations (i.e., building) limiting extrapolation to the wildland fire context. Inherent fluctuations in wildland firefighting conditions such as wind speeds, smoke, and radiant heat from the fire, make it difficult to examine the influence of restricted sleep and ambient temperature on cognitive performance. A controlled laboratory simulation is one compromise.

Other studies focussing on the effects of consecutive days of sleep restriction have revealed deficits in cognitive performance relative to the amount of sleep obtained (Belenky et al., 2003; Van Dongen, Maislin, et al., 2003). There remains however, a gap in the laboratory

research literature in relation to the effects of restricted sleep with concomitant physical activity and variations in ambient temperature on cognitive performance. Other research on physically challenging occupations such as sustained military operations shows that cognitive performance will be impaired with sleep loss and physical activity in extreme weather, although these studies are difficult to compare as they often initiate sleep restriction with a period of total sleep deprivation (Haslam, 1982; Lieberman, Bathalon, Falco, Kramer, et al., 2005). If firefighters are unable to preserve their cognitive performance between consecutive shifts then fire agencies need to employ fatigue risk management strategies to protect firefighter worker safety and productivity. Furthermore, impaired cognitive function under sleep restriction with adverse temperatures may compromise not only the individual health and safety of the firefighter on the fireground but increase overall demands on the rest of the crew.

1.3 Thesis objectives

The overall aim of this thesis was to investigate the interactions between firefighters' sleep, ambient temperature, hydration status, and cognitive performance during simulated single and multi-day wildfire suppressions. These exact aims are addressed through four studies:

1. To assess the effect of ambient heat during day-(33-35°C) and night-time (23-25°C) exposures on firefighters' sleep quantity and quality during a simulated multi-day wildfire suppression compared to thermoneutral temperatures (18-20°C; Study 1 - Chapter 4).
2. To quantify the effect of sleep restriction in either ambient heat with day- (33-35°C) and night-time (23-25°C) exposures or thermoneutral conditions (18-20°C) on firefighters' sleep architecture during a simulated multi-day wildfire suppression compared to a control condition with normal sleep in temperate conditions (18-20°C; Study 2 –Chapter 5).
3. To examine the association between firefighters' hydration status and cognitive performance during a simulated prolonged wildfire suppression shift in the heat (33-35°C) compared to thermoneutral temperatures (18-20°C; Study 3 –Chapter 6).
4. To examine the effect on cognitive performance of sleep restriction in either ambient heat with day-(33-35°C) and night-time (18-20°C) temperature changes or temperate conditions (18-20°C) during a simulated multi-day wildfire suppression compared to

a control condition with full sleep opportunities in thermoneutral temperatures (18-20°C; Study 4 –Chapter 7).

1.4 Significance of the research

As wildfires are on the increase in frequency and severity (Liu et al., 2010) there may be a need for longer and more frequent deployments. In the absence of an increase in the number of volunteer wildland firefighters, this highlights a significant issue for suppression activities. Maintaining wildland firefighting effectiveness into the future requires underpinning evidence to support appropriate occupational practices, policies and procedures. High levels of firefighter mental fatigue or cognitive impairment could potentially result in decreased worker productivity and efficiency, or elevated risk of injury. This in turn places an increased demand on the other supporting crewmembers and deteriorates the overall operational efficiency of the fire suppression efforts. The current research will provide fire agencies with psychological and physiological data in response to challenges posed by sleep restriction, high ambient temperatures, hydration status and mental function. The aim is to provide fire agencies with new evidence to inform policy makers on workforce fatigue risk management strategies.

This thesis aims to utilise a laboratory based simulation of wildland firefighting to provide new data for interpreting the relationships between temperature, sleep, hydration status, and cognitive performance. However, the contribution of this research to the literature is not limited to wildland firefighting operations. Rather, it adds value to the existing literature relating to the measurement of sleep, hydration status and cognitive performance of personnel from a wide range of industry and contexts. Whilst field studies are always preferred, laboratory and simulation studies are the most commonly used when addressing these questions. One of the benefits of such conditions is unlike field studies they are not confounded by extraneous variables such as changing fire conditions and highly fluctuating daily temperatures. Yet, laboratory studies are also limited in that they employ exercise protocols (for e.g., treadmill walking) that do not mimic the work-to-rest ratios, durations or types of movements characteristic of wildfire suppression. To overcome these limitations, this thesis will utilise a novel, high-fidelity simulation based on real-life wildland firefighting

scenarios to inform on the interrelationship between temperature, sleep, hydration status and cognitive performance. This presents the ideal testing scenario for such questions.

Chapter 2: Review of the Relevant Literature

2.1 Wildland firefighting and sleep

2.1.1 Occupational and environmental stressors effecting sleep in wildland firefighters

Australia is known as one of the more fire devastated countries worldwide, with rural and regional areas particularly susceptible to wildfire (Hennessy et al., 2005; Liu et al., 2010). Australia's hot and dry summers with low humidity and high wind speeds, in addition to low rates of precipitation each year, result in the increased risk of catastrophic wildfires (Aisbett et al., 2012). It is estimated that over 700 lives have been lost in the last 150 years of documented Australian wildfires, with costs in excess of two and a half billion dollars from wildland fire suppression and recovery efforts (Haynes, Handmer, McAneney, Tibbits, & Coates, 2010).

Importantly for fire agencies and rural communities, wildland fires are only predicted to increase in frequency, duration and severity due to the changing conditions of the global climate with a shift towards hotter, drier summers (Liu et al., 2010; Westerling, Hidalgo, Cayan, & Swetnam, 2006). An increase in wildfire activity around Australia will likely result in greater demands being placed on the services of wildland firefighters and fire agencies whose role it is to protect Australian societies from loss of infrastructure, farmland, cattle and produce (Hunter, 2003; Hyde et al., 2007). The largely rural and regional personnel constituting the Australian wildfire populace consists of approximately 220,000 younger and older people, 83% males and 17% females, with the vast majority volunteers (99.9%; McLennan & Birch, 2005). It is essential that all available steps are taken to protect the health and safety of this workforce, and optimise performance of their suppression operations.

Wildfires can last for hours, days or even weeks, requiring 24 h round the clock suppression and recovery efforts to be carried out, largely using traditional shift work rosters. Traditional rosters provide one 12 h period of work and one 12 h period of rest with 24 h coverage achieved by two fire crews working in 12 h on/12 h off rotations (Aisbett et al., 2012). The duration of shifts and the number of shifts in a row worked by personnel is specific to each international fire agency and also to each Australian state agency (Cater et al., 2007; Rodriguez-Marroyo et al., 2012). Within Australia, wildland firefighters are predominantly

required to work 12 h day- or night shifts, however shifts can extend to 16 h in length (Cater et al., 2007). Long work days, including nights, decrease the opportunity for firefighters to obtain rest between consecutive shifts, often resulting in decreased total sleep time (TST) between successive work periods (Vincent et al., 2016). Furthermore, sleep opportunities may also be reduced if there are insufficient replacement crews or individual personnel, as firefighters already on-shift have to extend their work period to maintain operations (Cater et al., 2007; Gaskill & Ruby, 2004).

During wildland fireground deployments firefighters may also sleep in temporary accommodations located either on or near the fireground (Cater et al., 2007; Gaskill & Ruby, 2004). Adverse sleep conditions on the fireground accommodation site may be due to noise from power generators, projection lights, hot, humid, and or smoky conditions; all factors that can lead to a decline in sleep quantity and quality (Aisbett et al., 2012; Vincent et al., 2016). Simply sleeping away from home in unfamiliar surroundings may be enough to adversely impact sleep (Jay, Aisbett, Sprajcer, & Ferguson, 2015; Vincent et al., 2016). Thus wildland firefighters regularly obtain inadequate sleep during wildfire suppression. This accumulation of sleep loss over consecutive days is also commonly encountered in other emergency service occupations including police and paramedics (Vincent et al., 2016).

There is little research examining firefighters' sleep quantity and quality during multi-day simulated wildfire suppressions (Vincent et al., 2016). This is most likely due to the practical impositions of collecting valid and reliable sleep data in the field without limiting an individual firefighter's work efforts or detracting from the overall fire suppression operations. Furthermore, the effect of environmental and occupational stressors on a firefighter's sleep architecture could have important implications for the following days' work productivity estimates both physically and mentally. In addition, understanding the specific impacts on sleep may also benefit firefighter health and safety (Aisbett et al., 2012). Where research is available on the effects on firefighters' sleep during multi-day wildfire suppression, it has focused on either subjective measures, such as self-report questionnaires, or objective measurements including activity monitoring. Research examining the effect of occupational and environmental stressors such as sleep restriction, physical activity, and extreme ambient temperatures on specific sleep stages and patterns does not exist, either for firefighters, in the laboratory or the field. Instead, information drawn primarily from laboratory, sports-science, exercise and military studies provides some insight into the effect of individual and

combinations of stressors such as sleep loss or extreme weather conditions on sleep architecture.

2.1.2 Sleep behaviours of wildland firefighters during wildfire suppression

Presently there are only three published studies on firefighters' sleep during wildfire suppression in the field (Cater et al., 2007; Gaskill & Ruby, 2004; Vincent et al., 2016). Previous research on Australian land management firefighting during wildfire suppression operations using structured interviews and post-fire suppression debriefs with both male and female career firefighting specialists revealed a number of factors related to fatigue (Cater et al., 2007). From this research, shift lengths of over approximately 14 h for both day and night shift rosters were identified, in addition to wakefulness in excess of 24 h as a response to the initial fire suppression operation (Cater et al., 2007). The potential reasons for excessive wakefulness on the first day of the deployment were not discussed although it is not uncommon for volunteer firefighters to respond to an emergency after already having completed a normal days' work at their regular routine employment (McLennan & Birch, 2005; Vincent et al., 2016). More importantly, firefighters interviewed post-deployment reported having obtained an average duration of 3 h to 6 h sleep per shift (Cater et al., 2007). Moreover, firefighters also anecdotally reported driving up to 3 h after already having done a 16 h shift on the fireground, posing an increased risk of fatigue related accident or injury whilst driving due to sleep loss (Cater et al., 2007). A number of other factors related to increased fatigue were also identified including the sleep accommodation conditions and site, and the quality and length of sleep for night-shift personnel (Cater et al., 2007).

A second field study on firefighter's sleep investigated 56 North American wildland firefighting crews, with both male (*n* [number] = 47) and female (*n* = 9) firefighters, during random duty deployments in the wildland fire season (Gaskill & Ruby, 2004). Firefighters completed a sleep recall questionnaire regarding the duration of sleep, their time to sleep and time to wake on a daily basis each morning during the deployment. From 276 nights of self-reports the average number of hours (h) slept each night was: less than 6 h (13%), 6 h to 7 h (27%), 7 h to 8 h (28%) and more than 8 h (32%). Alarmingly a small percentage (approximately 5%) of firefighters reported obtaining 3 h to 4 h sleep or 4 h to 5 h sleep (also

approximately 5%). There was no follow-up investigation so the reasons for the sleep loss is not known (Gaskill & Ruby, 2004).

A third field study on firefighters' sleep focused on objective measures including activity monitoring as a method to examine firefighters' sleep during wildfire suppression deployments (Vincent et al., 2016). Vincent and colleagues reported that sleep was restricted during multiple wildfire suppression days to 6.1 h, 54 minutes less than on non-fire days. In contrast, subjective ratings of sleep quality, latency, efficiency and the number of times awoken during the night did not significantly differ between work and non-work days. The findings showed that TST decreased in association with a number of factors including shift lengths exceeding 14 h, or shifts starting in the early morning hours (i.e., 05:00 h to 06:00 h) or if firefighters were required to sleep in tents or their vehicles following the completion of a shift. The authors' conclusion, aimed primarily at fire agencies was that whilst sleep time is restricted during wildfire suppression, optimal sleep opportunities may be afforded by altering certain characteristics of work shifts (i.e., not exceeding 14 h) and the sleeping environment for firefighters (for e.g., sleep in nearby motels and accommodations; Vincent et al., 2016).

Collectively these studies suggest that many firefighters experience sleep loss during multi-day wildfire suppression deployments with some studies reporting 6 h or less as a common average (Cater et al., 2007; Vincent et al., 2016). However, these studies share a major inherent limitation in utilising self-report measures of sleep quantity, as normal healthy sleepers have been shown to overestimate sleep time on subjective measures as they are usually unaware of the precise time of sleep onset (Fichten, Creti, Amsel, Bailes, & Libman, 2005). The only study to utilise objective measures of activity monitoring by Vincent et al. (2016) provides valuable information on the TST and other quantitative measures of wildland firefighters during deployments although does not reveal the actual time spent in each stage of sleep. More importantly, activity monitoring has its own inherent limitations due to calculations often including periods of quiescent wakefulness. That is, when where there is little movement or physical activity, this is often erroneously analysed and included as TST (Pollak, Tryon, Nagaraja, & Dzwonczyk, 2001). However, this research indicates that sleep restriction in the wildland firefighter population is a significant occupational and environmental stressor, although the sleep architecture and specifically the sleep stages of this workforce have not yet been documented under any circumstances, either in the field or

in the laboratory. One reason for this may be the difficulty in recording a firefighter's sleep on the fireground in extreme environmental wildfire conditions (Jay et al., 2015). This requires a method that does not interfere with the individual's sleep, and next day work productivity and performance as well as other crewmembers involved in the ongoing overall fire suppression operations.

Ambulatory technologies such as portable polysomnography devices provide a suitable, feasible and practical way to measure sleep and give a more accurate and reliable assessment of sleep than activity monitoring or subjective self-report measures. Research on the effects of multi-day wildfire suppression on the resulting sleep patterns and the amount of time spent in each stage of sleep would provide critical information relevant for managing health, safety and productivity. Despite there being no research on the types of occupational and environmental stressors encountered during wildfires such as physical activity, ambient temperature, and sleep loss, similarly designed laboratory, sports-exercise, industry and military studies provide some insight on the impacts of these stressors on sleep architecture. But first it is necessary to provide an explanation of the stages of sleep, how they are measured, the sleep architecture of a normal healthy young adult during a typical nights' sleep and an introduction to the two-process model of sleep-wake regulation.

2.1.3 Introduction to sleep

The field of sleep research has been the subject of extensive scientific inquiry for the past 120 years, with the first published studies of total sleep loss dating back to 1894 in dog puppies (de Manaceine, 1894) and 1896 in humans (Patrick & Gilbert, 1896). Whilst the human study largely paved the way for the measurement of physiological and behavioral assays of sleep variables still applicable in modern standards today, it was ultimately the puppy study that reinforced the idea that prolonged sleep loss in mammals could be fatal. The following century would establish large bodies of research arising from the multi-disciplinary approaches of biology to medicine, physiology even psychology, producing literally an A to Z checklist of topics in sleep research - from Alexander A. Borbély's (1982) two-process model of sleep regulation, to zeitgebers, the signals that entrain the sleep-wake cycle (Aschoff, 1965). The field of sleep research is unequivocally diverse and rich, with an equally detailed history.

2.1.4 Sleep, definition, stages, measurement and classification

Sleep, according to a widely cited simple behavioural description, can be defined as “a reversible behavioural state of perceptual disengagement from and unresponsiveness to the environment … a complex amalgam of physiological and behavioural processes” (Carskadon & Dement, 2011, p. 16). Behaviourally, sleep is accompanied by postural recumbence, physical quiescence and closed eyes. However physiologically, sleep is a dynamic process, so although the body is in a state of relative inactivity, neuronal activity is subject to a range of cyclical changes with electrophysiologically distinct stages (Carskadon & Dement, 2011). The monitoring of these distinct changes in the electrical activity of the brain allows differentiation by arousal thresholds and depth of sleep to then quantify and classify sleep into stages (Ogilvie & Wilkinson, 1984).

The discovery of electrical rhythms was pioneered by Scottish physiologist Richard Caton in 1875 although it was not until 1928 that German psychiatrist Hans Berger would develop what is known today as the electroencephalogram (EEG; Dement, 2011). Berger was able to clearly demonstrate the marked differences in neuronal rhythm recordings of human beings in states of wake and sleep, providing the first continuous quantitative measurement of sleep (Dement, 2011). Then in 1968, Rechtschaffen and Kales published *A manual of standardised terminology, techniques and scoring system for sleep stages of human subjects* providing the first uniform means to comparatively measure sleep in clinical and scientific settings. Sleep was characterised into two states of rapid-eye movement (REM) and non-REM (NREM) into Stages 1, 2, 3, and 4 sleep, (Rechtschaffen & Kales, 1968).

Revisions have since been made to these original scoring criteria in 2007 by the American Academy of Sleep Medicine (AASM) to incoporate alternatives in the scoring of sleep related events through the specifications of arousal, cardiac, movement and respiratory rules. The new AASM sleep scoring criteria revised Stages 1 through to Stage 4 sleep into N1, N2, and N3. Stage 3 and Stage 4 sleep are combined to form the revised Stage N3, whilst N1 and N2 reflect Stage 1 and Stage 2 sleep, respectively, and REM sleep is referred to as R. The majority of literature on sleep utilised the original Rechtschaffen and Kales (1968) scoring criteria. All research discussed herein refer to their original scoring terminology, unless otherwise speficifically stated.

Wakefulness by default is merely the absence of sleep and is physiologically defined by the presence of alpha activity (8-13 hertz [Hz]) with a relatively low-voltage and mixed frequency constituting the majority of the EEG (Carskadon & Dement, 2011). Wakefulness typically accounts for under 5% of a normal nocturnal habitual sleep opportunity (Feinberg & Floyd, 1979). A relaxed state of wakefulness precedes sleep onset that usually occurs within seconds to minutes after the appearance of slow eye rolling movements in the electro-oculogram (EOG) and is typically concurrent with a gradual decline or 'tonic' in muscle tonus and activity in the electromyogram (EMG; Rechtschaffen & Kales, 1968). The precise definition of sleep onset is difficult as no single sleep measurement indicates 100% of the time that sleep onset has occurred. That is because even when the EEG indicates an individual is in Stage 1 sleep they will often subjectively report that they were still awake. Therefore, the presence of k-complexes, or sleep spindles, that are actually indicative of Stage 2 sleep will often be used to identify sleep onset (Carskadon & Dement, 2011).

A sleep cycle can be defined as the period taken for one complete oscillation of NREM and REM sleep, in healthy young adults, with a set sleep pattern of 8 h nocturnal sleep, the first cycle of sleep is entered through NREM sleep, and usually lasts around 90 minutes on average (Carskadon & Dement, 2011). The pattern of sleep Stages 1,2,3,4 and REM across the night is also associated with increasing levels of magnitude in the arousal threshold required to physically 'wake' participants (Carlson, 1991; Carskadon & Dement, 2011). This has been demonstrated through studies showing additive or cumulative increases in external stimuli needed to elicit an arousal response from sleeping participants (Carlson, 1991).

Stage 1 (NREM) sleep is known as the transitional state as it encompasses the initial wake to sleep change over period and commonly occurs as a transitional stage throughout the night (Carskadon & Dement, 2011). Stage 1 sleep is characterised by a decrease in alpha activity with a relatively low voltage, mixed frequency EEG (2-7 Hz) with sharp vertex waves (see Figure 2.1). On average Stage 1 sleep usually accounts for 2-5% of a healthy adult's habitual nocturnal sleep and has a duration of one to seven minutes at sleep onset that is usually accompanied by involuntary physical movements (for e.g., slow rolling-eye movements and involuntary limb twitches; Rechtschaffen & Kales, 1968). Stage 1 sleep is also associated with a low arousal threshold and is effortlessly interrupted by subtle activity e.g., quietly closing the bedroom door.

Stage 2 (NREM) sleep is considered as the state of 'true sleep', and as such is the stage marking sleep onset, typically accounting for 45-55% of a normal night's sleep (Carskadon & Dement, 2011; Rechtschaffen & Kales, 1968). Stage 2 sleep is characterised by a low voltage, mixed frequency EEG, with a duration of 10 to 25 minutes (Carskadon & Dement, 2011; Rechtschaffen & Kales, 1968). Stage 2 sleep is distinguished by the visual appearance of sleep spindles, shown as 0.5 - 1.5 seconds of EEG with phasic bursts of sigma activity at 12-14 Hz (see Figure 2.1). K-complexes may come in bursts with sleep spindles or appear alone. K-complexes are visually sharp EEG waveforms of less than or equal to 0.5 seconds in duration with clearly observable negative and positive acute vertexes and troughs of shortened wavelength and increased amplitude (Rechtschaffen & Kales, 1968). The arousal threshold is also higher with stimuli that would result in awakening from Stage 1 sleep typically producing evoked K-complexes but no awakening from Stage 2 sleep (Carskadon & Dement, 2011).

Stage 3 and 4 (NREM) sleep are collectively referred to as slow-wave sleep (SWS), delta activity, or deep sleep and are characterised by high-voltage (< 3 Hz), delta waves (see Figure 2.1). As Stage 2 sleep progresses, high-voltage slow wave activity emerges in the EEG and as the proportion increases, the criteria for Stage 3 sleep are met. Stage 3 sleep is defined when more than 20%, but less than 50% of one 30 second epoch of sleep EEG activity consists of high-voltage delta waves (75 microvolt's [µV]) and slow-wave activity (SWA; 0.5-2 Hz; Rechtschaffen & Kales, 1968). Stage 3 sleep only lasts a few minutes in the first sleep cycle, functioning as a brief transitional state to Stage 4 sleep. Stage 4 sleep is defined by high-voltage SWA constituting 50% of EEG activity for one 30 second of a sleep epoch which satisfies the standard criteria of a putative marker of homeostasis having been met (Rechtschaffen & Kales, 1968). Stage 4 sleep has a duration of 20 to 40 minutes in the first sleep cycle with SWS usually accounting for 20-25% of a normal nocturnal sleep (Carskadon & Dement, 2011). Eye movements are typically restricted, during Stage 3 and 4 sleep however the EOG usually mimics high-voltage SWA present in the EEG. Once again a considerably more intense stimulus is needed to provoke arousal from Stage 3 and 4 sleep compared to Stage 1 or 2 sleep (Carskadon & Dement, 2011).

Collectively Stage 1,2,3 and 4 sleep or NREM sleep, may serve a function in physical restoration and energy conservation (Adam & Oswald, 1983; Akerstedt & Nilsson, 2003;

Horne, 1988; Horne, 1985). This is due to the finding that SWS occurs concurrently with a decline in body temperature, oxygen intake and heart rate (Shapiro & Flanigan, 1993). Additionally the Delta waves shown during SWS are actually biologically produced by the cerebral cortex, that is, the primary brain area responsible for mental functioning while awake, in addition to thalamocortical loops theorised responsible as other brain regions responsible for mental functioning (Llinás, 2003; Mitra et al., 2016; Shapiro & Flanigan, 1993). The cerebral cortex controls mental functions such as memory, attention, spatial and perceptual awareness, syntax, semantics or grammatical reasoning, language and generally all cognition or human consciousness (Halliday et al., 2018). Similarly, thalamocortical interconnectivity, and more specifically the function of the thalamocortical loop, suggests that the thalamus is actually a site of inter-communication between the cerebral cortex and all other brain sites, essentially responsible for generating the functional states that give rise to human cognition (Llinás, 2003). So then it is not surprising to find that all these cognitive functions decline when there is sleep loss as further discussed in Section 2.3 (Belenky et al., 2003; Van Dongen, Maislin, et al., 2003).

A series of body arousals such as involuntary leg twitches and arm movements, changes in depth of breathing and sometimes EMG tonal activation mark an individual's transition into the lighter stages of sleep, providing an indicator that the first REM episode is about to commence (Carskadon & Dement, 2011; Shapiro & Flanigan, 1993). Physiologically the EEG will typically display one to two minutes of Stage 3 sleep, followed by five to 10 minutes of Stage 2 sleep, before the first REM episode commences. REM sleep is a state that has been objectively shown to co-occur with suppressed muscle tension registered by EMG activity and also more interestingly dreams, which may be reflective of REM's relatively heightened brain activity compared to Stages 1,2,3 and 4 sleep (Dement & Kleitman, 1957). REM sleep is characterised by tonic suppression of skeletal muscle tone and an EEG of low-voltage mixed frequency theta activity (3-7 Hz) with instances of slow alpha activity (8-12 Hz; see Figure 2.1) and also muscle twitches arising as phasic muscle activation on the EEG. REM sleep is distinguishable from NREM sleep classically by the presence of rapid eye movements in the EOG (Rechtschaffen & Kales, 1968). REM sleep during the first cycle is of short duration, usually between one and five minutes. The arousal threshold for REM sleep varies, as does REM sleep throughout the night usually accounting for 20-25% of a normal night-time sleep. REM sleep is not conventionally divided into stages, however two types exist for scientific classification, phasic versus tonic, and are distinguishable by either the

presence of high levels of EOG activity, or the absence of eye movements, respectively (Carskadon & Dement, 2011).

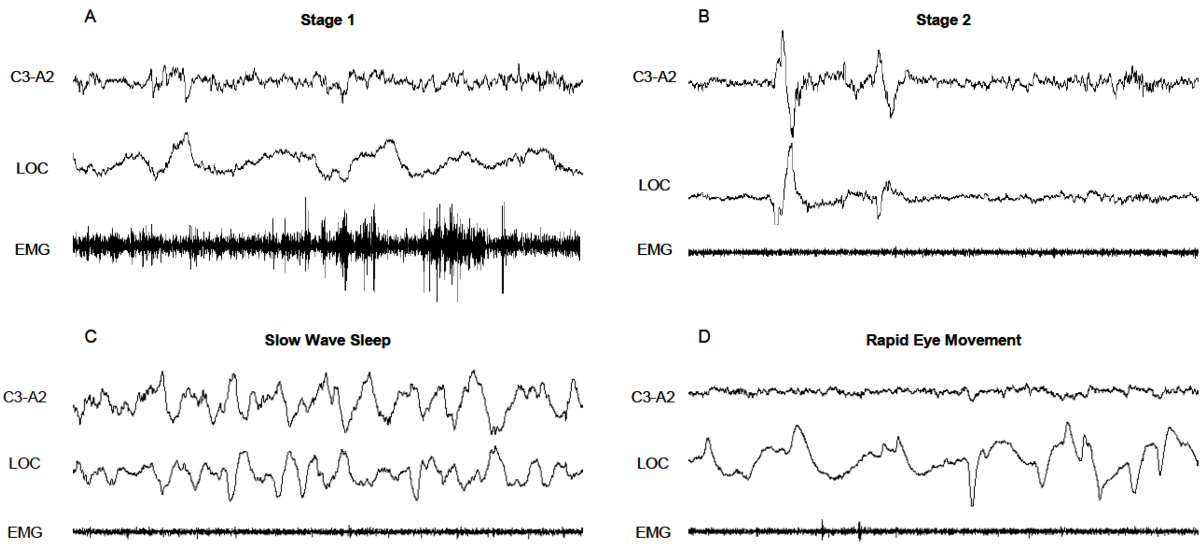

Figure 2.1 Electroencephalographic (EEG; C3-A2) output of the sleep stages. A) Stage 1 mixed frequency EEG, slow left outer canthi (LOC) movement with high electromyogram (EMG) activity; B) Stage 2 with K-complexes and a sleep spindle C) Slow-wave sleep (SWS); D) Rapid eye movement (REM) in LOC, with low EEG and EMG activity.

2.1.5 Pattern of a normal night's sleep

A normal sleep duration of 8 h, in a healthy young adult with no sleep abnormalities, will tend to follow a general NREM-REM cyclical pattern with no consistent sex differences present in young adults (see Figure 2.2; Carskadon & Dement, 2011). The average cycle of the first NREM-REM sleep is roughly 70 to 100 minutes, with SWS dominating the NREM segment of the sleep cycle in the earlier portion of the night's sleep and REM episodes longest in duration in the latter portion of the night's sleep (Carskadon & Dement, 2011). The average length of the second cycle of NREM-REM sleep is 90 to 120 minutes (Carskadon & Dement, 2011). The second cycle is characterised by reductions in Stage 3 and 4 sleep, which may be absent altogether from later cycles as the duration of Stage 2 sleep increases to engulf the NREM portion of the sleep cycle (Carskadon & Dement, 2011). Over the course of a normal night's sleep the mean length of the NREM-REM cycle lasts around 90 to 110 minutes, with a sleep period usually consisting of up to four or five NREM-REM cycles, the

characteristics of these sleep cycles are what is known as ‘sleep architecture’ (Carskadon & Dement, 2011).

Throughout the course of a typical night-time sleep period an individual will enter sleep through NREM, usually Stage 1 and will spend 75-80% of the major sleep episode in NREM sleep (Carskadon & Dement, 2011). As mentioned broadly in Section 2.1.4 and summarised here this percentage consists of 2-5%, 45-55%, 3-8%, and 10-15% of time spent in NREM Stages, 1, 2, 3 and 4, respectively (Carskadon & Dement, 2011). REM constitutes the other 20-25% of sleep over four to six discrete episodes, with less than 5% of the time spent awake after sleep onset (Carskadon & Dement, 2011). Wakefulness usually occurs as a brief episode near the REM sleep transitions. The normal distribution of SWS that is obtained in the first one-third of the major sleep episode is thought to be due to the homeostatic regulation component of sleep and is a marked response to the duration of prior wakefulness (Carlson, 1991; Shapiro & Flanigan, 1993). Conversely, the preferential distribution of REM sleep toward the latter one third of the night is thought to be due to a circadian process closely associated with the rising phase of core body temperature (Czeisler et al., 1999). These homeostatic and circadian rhythm processes form the foundations of Borbely’s (1982) two-process model of sleep regulation as discussed in Section 2.1.7.

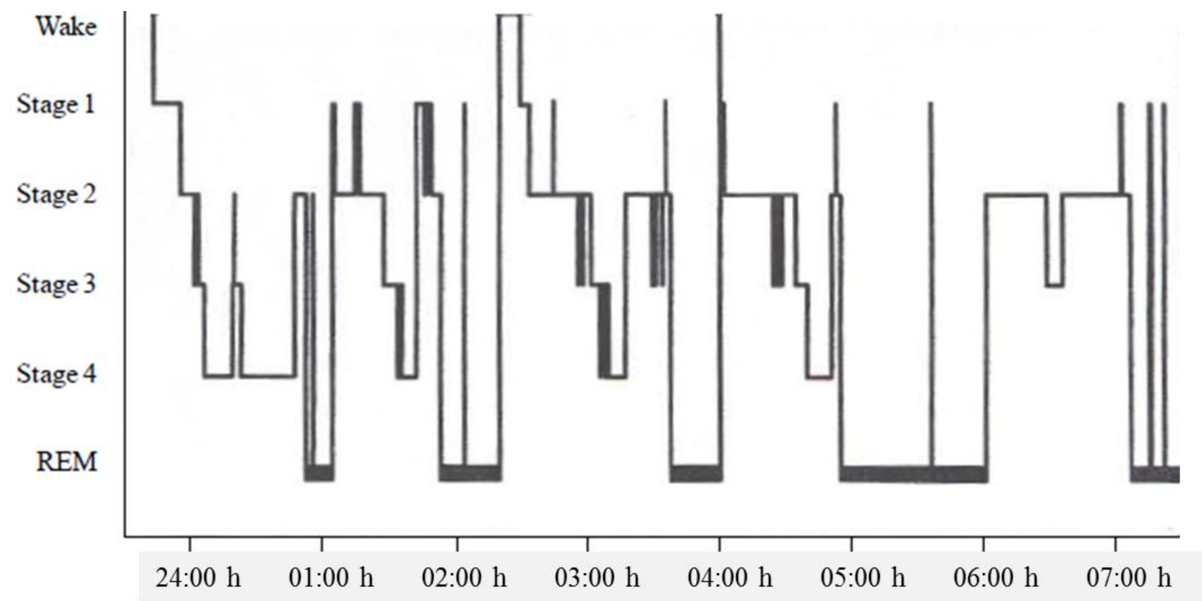

Figure 2.2 The progression and distribution of sleep stages throughout an 8 h night-time sleep in a healthy normal young adult (Figure recreated from Carskadon & Dement, 2011).

2.1.6 Sleep requirements

The required duration of sleep has been an existing debate for decades. The core-sleep hypothesis, originally delineated by Horne (1988) posits a ‘core’ of 4 h to 5 h sleep is required for optimal daily functioning, and is usually obtained in the first three cycles of sleep. As such sleep beyond the proposed 4 h to 5 h core requirements is labelled as ‘optional’ sleep, and could essentially be removed without consequence for daytime functioning and alertness. Later, Horne revised this amount of ‘core’ sleep, to 6 h of good quality uninterrupted sleep (Horne, 1988). Nonetheless, sleep research using a chronic sleep restriction protocol has demonstrated that when sleep opportunity is restricted to less than 6 h per night this results in significant deteriorations in daytime cognitive functioning (Van Dongen, Maislin, et al., 2003) and establishing 8.16 h of sleep as the critical duration of sleep required for a “maximum period of stable waking neurobehavioral functioning” (Van Dongen, Maislin, et al., 2003, p. 123). So whilst guidelines are present, generally the exact amount of sleep required will fall within a range depending on the individual person’s needs (Van Dongen, Maislin, et al., 2003; Van Dongen, Rogers, & Dinges, 2003). Presently, the National Sleep Foundation recommends adults aged between 18 and 64 years (y) should aim for 7 h to 9 h as a general guide (Hirshkowitz et al., 2015).

2.1.7 The two-process model of sleep regulation

Two key physiological processes have been identified in regulating the sleep-wake cycle in order to maintain homeostatic sleep pressure that is synchronised to the exogenous 24 h solar-day light/dark cycle (Achermann, 2004). As originally delineated by Borbely (1982) and recently revised by Borbely, Daan, Wirz-Justice, and Deboer (2016) these two processes are known as the circadian process or Process C and a homeostatic sleep drive or ‘sleep pressure’, labelled as process S (see Figure 2.3). The circadian process is determined by biological rhythms, and is measurable via core body temperature (Czeisler et al., 1999). The rhythm is reflective of a sinusoidal wave that varies the pressure for wakefulness throughout the 24 h day/night continuum (see Figure 2.3, Process C and also Section 2.1.8 Circadian rhythms). Homeostatic sleep pressure or process S (see Figure 2.3), determines the onset and termination of sleep. The propensity for sleep increases as a function of time from the point of awakening and eventually results in sleep onset, then this pressure decreases as a function

of time asleep (Borbely, 1982; Borbely et al., 2016; Kryger, Roth, & Dement, 2010). Figure 2.3 shows the two-process model of sleep regulation, demonstrating the effects of Process C and Process S over the course of a 48 h diurnal period of the sleep-wake cycle.

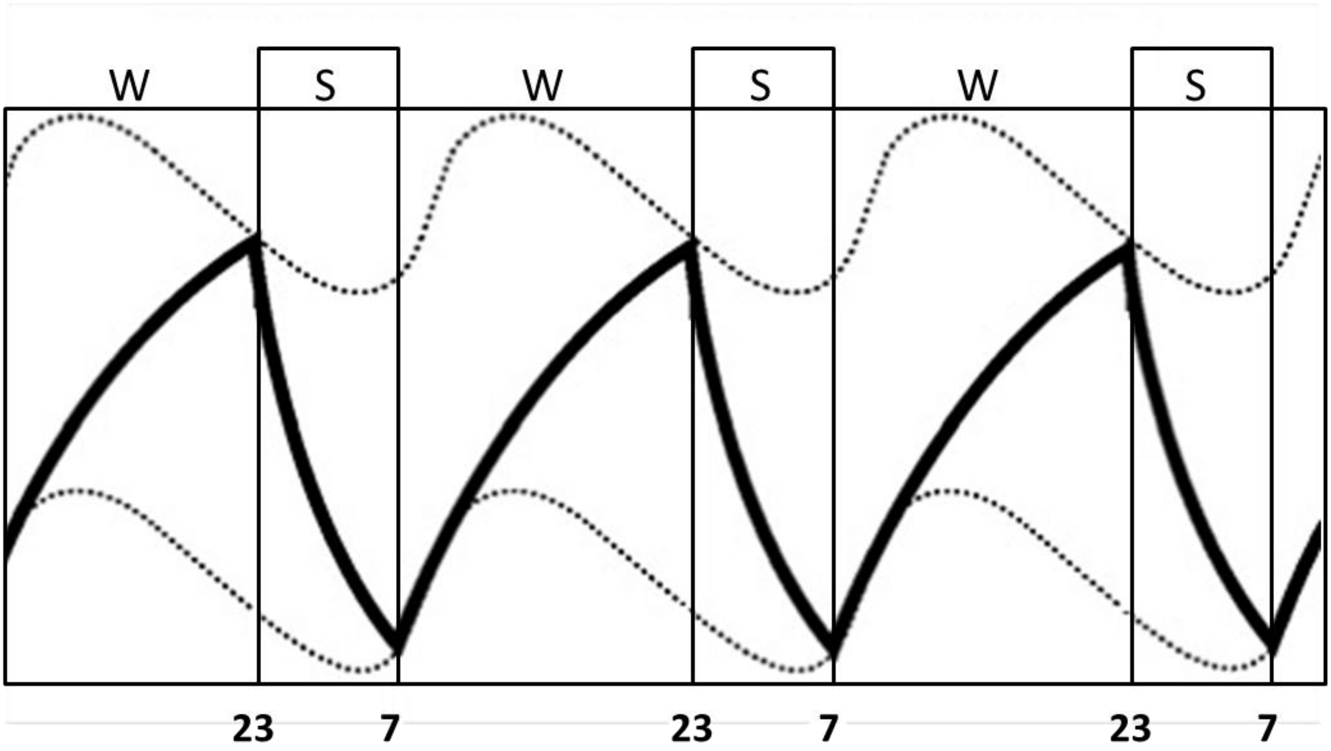

Figure 2.3 The two-process model of sleep regulation. S delineates ‘sleep’, whilst W represents ‘wake’. The homeostatic sleep pressure or process S (bold lines) accumulates with hours of prior wakefulness between 07:00 h until 23:00 h and then decreases as a function of time asleep during a typical normal nights’ rest between 23:00 h and 07:00 h. The circadian process C (dotted lines) varies as a function of time-of-day rising and peaking with the acrophase occurring during the late evening and the bathyphase or falling limb and nadir of the circadian cycle occurring during the night-time (Figure recreated from Beersma & Gordijn, 2007).

2.1.8 Circadian rhythms

The term circadian is derived from the Latin ‘circa-dies’, with the literal meaning ‘about-a day’, reflecting the natural observation that many mammalian circadian systems oscillate with a period of approximately 24 h. Circadian rhythmicity is seen in a host of physiological and behavioural functions (Aschoff, 1965, 1988). The suprachiasmatic nucleus (SCN) is

recognised as the site of the endogenous circadian pacemaker or ‘master circadian clock’, and is located in the anterior hypothalamus, cycling with an average period of 24.18 h, although this varies slightly between individuals (Czeisler et al., 1999). Evidence for the anterior hypothalamus as the site of the SCN is demonstrated through studies showing that damage to the SCN in rats and lesions in squirrel monkeys manifests in a loss of circadian rhythms (Eastman, Mistlberger, & Rechtschaffen, 1984; Rusak & Zucker, 1979). While the SCN is not the only circadian clock (there are also numerous peripheral clocks), there is no controversy surrounding its role in the initiation and maintenance of mammalian circadian process (Rusak & Zucker, 1979). Not surprisingly then, is the finding that circadian rhythms have been shown to influence both sleep architecture and also neurobehavioral performance, with changes in the stages of sleep and cognitive performance closely associated with, and directly proportional to, changes in core body temperature (Czeisler, Weitzman, Moore-Ede, Zimmerman, & Knauer, 1980; Darwent et al., 2010; Dijk, Duffy, & Czeisler, 2000).

Core body temperature (CBT) allows a continuous observation of circadian phase providing the ‘gold standard’ in terms of reliability and validity, although is not employable during field research due to masking effects from externally generated heat, movement and posture (Campbell & Murphy, 2007; Czeisler et al., 1999). CBT displays a diurnal rhythm in persons with a normal healthy nocturnal set sleep schedule of between 7 h to 9 h with a typical average of 8 h sleep (see Figure 2.3). CBT slowly rises in the late afternoon, reaching the acrophase in the early evening, and then gradually decrease thereafter. The down phase occurs approximately between 23:00 h to 24:00/00:00 h, typically coinciding with sleep onset (see Figure 2.3; Czeisler et al., 1999; Dijk et al., 2000). CBT reaches the nadir or trough in the early hours of the morning (04:00 h to 05:00 h), usually coinciding with a major REM episode and steadily rises thereafter until awakening (around 06:00 h to 08:00 h), this is known as the bathyphase (Beersma & Gordijn, 2007; Czeisler, Zimmerman, Ronda, Moore-Ede, & Weitzman, 1980; Hirshkowitz et al., 2015). More generally, sleep propensity is highest during the circadian nadir when CBT is at its lowest point. Also coinciding with the phase of the circadian rhythm when neurocognitive performance and alertness are at their lowest point, which is due to the product of circadian variation and sleep propensity as opposed to the diurnal rhythm (Darwent et al., 2010; Wyatt, Ritz-De Cecco, Czeisler, & Dijk, 1999). Wake onset typically occurs within several hours following the circadian nadir (Aschoff, 1965; Campbell & Murphy, 2007). Then the opposite effect of CBT is observed as the circadian cycle is on the rising phase. Concurrent with a gradual increase in CBT, there is

a marked decrease in sleep propensity resulting in relatively stable performance registered throughout the daytime on cognitive performance measures (Czeisler et al., 1999; Wyatt et al., 1999).

2.1.9 External regulation of circadian rhythms

Circadian rhythms are entrained to the 24 h solar-day light/dark cycle by what are referred to as zeitgebers, taking the literal meaning from the German translation 'zeit' as 'time' and 'geber' is 'to give', 'to give time' or 'time-giver'. Non-photic zeitgebers include physical exercise and activity, meal patterns, bedtime schedules and social interactions (Aschoff et al., 1971; Mistlberger & Skene, 2005). Light is commonly recognised as the primary zeitgeber as the signal is received at the retina, transferred directly to the SCN along the adjoining neuro-anatomical pathway, called the retinohypothalamic tract, subsequently entraining the SCN and all other circadian rhythms to the 24 h solar-day light/dark cycle (Arendt & Broadway, 1987).

2.1.10 Homeostatic sleep pressure

Acting in synchrony with the circadian Process C, is Process S, also referred to as homeostatic sleep pressure (Figure 2.3). Research supports the role of a homeostatic sleep process through the observation that depth of sleep and staging are determined by the amount of prior wakefulness, with sleep deprived individuals demonstrating increased SWS and a heightened arousal threshold during recovery sleep. From total sleep deprivation (TSD) research it has been shown that when wakefulness extends beyond the normal 16 h to 18 h day, homeostatic pressure for sleep continues to increase and is associated with a decrease in performance on a range of cognitive measures including the Go/Nogo and Stroop tasks (Cain, Silva, Chang, Ronda, & Duffy, 2011; Drummond, Paulus, & Tapert, 2006). Furthermore, increased sleep propensity due to TSD manifests in significantly shorter sleep latencies of less than five minutes when sleep is finally allowed (Caldwell & LeDuc, 1998; Carskadon & Dement, 1979). More importantly, the subsequent sleep recovery period is typically characterised by increases in SWS and SWA (Bonnet & Rosa, 1987; Johnson, 1975; Johnson, Naitoh, Moses, & Lubin, 1974; Kales et al., 1970; Lubin, Moses, Johnson, & Naitoh, 1974). This research suggests a rebound effect of SWS and SWA resulting in 'deeper' Stage 3 and 4 sleep as a result of the prior amount of sleep loss (Ferrara, De Gennaro, Casagrande, &

Bertini, 1999). Whilst TSD studies provide significant support for the role of a homeostatic sleep process, they represent an extreme deviation from a typical nights' sleep loss, whereas other studies using partial sleep restriction protocols provide a more accurate indication as to the effects on sleep architecture of routine sleep loss. This will be discussed in the following Section.

2.1.11 Effects on sleep architecture of sleep restriction

The effects of sleep restriction on sleep architecture from chronic sleep restriction protocols (i.e., more than five consecutive nights in a row) are well established with two seminal studies reporting similar findings (Belenky et al., 2003; Van Dongen, Maislin, et al., 2003). In the study by Belenky et al. (2003) a large sample of healthy younger and older males and females were provided with sleep opportunities of 3 h, 5 h, 7 h, or 9 h time in bed (TIB) for seven nights of sleep restriction. Results demonstrated that amounts of Stage 1, 2 and REM sleep declined in a dose-dependent pattern throughout the seven nights of sleep restriction in the 3 h and 5 h TIB groups, but not the 7 h TIB group (Belenky et al., 2003). The 9 h TIB group displayed a similar but opposite effect with increasing amounts of Stage 1 and REM sleep. Slow-wave sleep however did not significantly vary across groups as a function of TIB. Similarly, one of the most widely cited studies in sleep research (Van Dongen, Maislin, et al., 2003) randomised a large sample of healthy younger and older male and female adults to either 4 h, 6 h, or 8 h sleep opportunities for 14 nights. Results revealed immediate overall reductions in the amounts of Stage 1, 2 and REM sleep for the restriction conditions (i.e., 4 h and 6 h), whilst SWS was conserved with no statistically significant differences between groups. Additionally, REM latency significantly decreased over nights in the 4 h condition, but did not alter over nights of sleep restriction in the 8 h and 6 h conditions. The findings of these two seminal studies (Belenky et al., 2003; Van Dongen, Maislin, et al., 2003) are also consistent with results reported by earlier sleep restriction laboratory research showing reductions in the amounts of Stage 2 and REM sleep, whilst SWS was either conserved or enhanced (Dement & Greenberg, 1966; Mullaney, Johnson, Naitoh, Friedmann, & Globus, 1977; Webb & Agnew, 1974).

2.1.12 Effects on sleep architecture of exercise/physical activity

The effects of exercise on sleep architecture were first studied by Horne and Porter (1975) in a small sample of young healthy males performing moderate exercise at 45% of their maximum work load capacity, in either a morning or afternoon training session. Results revealed a time-of-day effect of exercise on the subsequent major sleep period, with increasing amounts of SWS during the first half of the night following afternoon exercise, counterbalanced by a non-significant decrease during the second half of the night, resulting in no overall significant change overnight in SWS. They concluded if a heavy but tolerable workload occurs early in the day, then the daytime period allows sufficient recovery such that sleep is unaffected. However, if the workload is conducted later in the day the period of wakefulness may not be sufficient for recovery, hence this process may intrude into the night reflected as increases in SWS and SWA prominent in the EEG. A subsequent study by Horne and Staff (1983) tested a small sample of young healthy males in the afternoon and early evening (14:00 h to 18:00 h) under three experimental conditions of high intensity exercise (80 minutes [mins] of running at 80% maximal oxygen consumption [VO_{2max}]), low intensity exercise (160 mins of running at 40% VO_{2max}) or passive heating (i.e., no exercise). Results revealed the low intensity exercise condition did not show any change in SWS although displayed a significant increase in sleep length and Stage 1 and 2 sleep with a decrease in sleep onset duration. In contrast the high intensity and passive heating conditions revealed a significant increase in Stage 3 and 4 sleep, or SWS, although REM sleep was not affected by any of the experimental conditions.

Two other studies by Horne and colleagues subjected a small sample of young female participants to two 40 minute afternoon (14:30 h to 17:30 h) running sessions (at an intensity of 75% VO_{2max}) with and without additional cooling (Horne & Moore, 1985) or two 90 minute afternoon sessions submerged in baths of warm or cool water (Horne & Reid, 1985). The results of these two studies revealed no effect on sleep architecture following either running with additional cooling or a cool temperature bath. Although their findings did show that running without additional cooling or a warm temperature bath was associated with significant increases in SWS and reductions in REM sleep. This series of studies by Horne and colleagues led them to conclude that a high and sustained 'heating up' of the body over 1 h to 2 h, as shown through a rapid rise in CBT, may trigger a SWS increase response. This occurs regardless of the method of induction i.e., passive heating (Horne & Staff, 1983), heated temperature baths (Horne & Reid, 1985) or intense exercise (Horne & Moore, 1985; Horne & Porter, 1975). The only potential limitation of this earlier research by Horne and

colleagues is the small sample sizes used for each study with no condition consisting of more than 8 males or 6 females under the age of 30 years.

2.1.13 Effects on sleep architecture of sleep restriction and physical activity

Haslam (1982) was one of the first to use a military simulation to study the combination of the effects of sleep restriction and physical activity on sleep architecture. This research involved a small sample of healthy young infantrymen during a nine day (216 h) tactical defence exercise. Participants were scheduled to an initial sleep deprivation period of 90 h, followed by 4 h sleep (from 01:45 h to 05:45 h) for six consecutive days. Military aspects of the trial included digging, camouflaging, and occupying trenches, surprise ‘enemy attacks’, mine laying and clearing in addition to first aid. EEG was monitored for all 10 participants throughout the entire exercise with a montage arrangement of four electrodes applied to the scalp and face (no EMG channel). Results revealed an increase in Stage 4 sleep following the 90 h of TSD, whilst percentage of REM and Stages 1 and 3 sleep remained almost constant and percentage of Stage 2 sleep was reduced. Overall, the results demonstrated that restoration of Stage 4 sleep is prioritised over REM during restricted sleep periods following sleep loss, consistent with early TSD and sleep restriction research (Johnson, 1975; Johnson & MacLeod, 1973; Johnson et al., 1974; Mullaney et al., 1977; Webb & Agnew, 1973, 1974). However, the major limitation of the study by Haslam (1982) is the absence of an EMG channel, making it more difficult to accurately differentiate between stages of sleep. EMG is most important for REM sleep, as it is distinctly marked by tonic, or the absence of facial muscle tone activation, that is revealed specifically by the EMG channel (Rechtschaffen & Kales, 1968).

2.1.14 Effects on sleep architecture of brief and continuous temperature exposures

The effects of brief or acute (i.e., less than three consecutive nights) temperature exposures on sleep architecture was first studied by Schmidt-Kessen and Kendel (1973) in a small sample of healthy young men sleeping in a climatic chamber at temperatures of 27 degrees Celsius (°C), 31°C or 36°C for a single night’s sleep. Results revealed that the lower the temperature of the room, the higher the percentage of REM and SWS. Results also showed

that warmer room temperatures were associated with higher percentages of wakefulness and REM latency, in addition to increased physical bodily movement during sleep. Consistent with these findings, a later study also demonstrated that increasing ambient temperatures from 32°C to 39.5°C resulted in an increased number of awakenings throughout the night (Henane, Buguet, Roussel, & Bittel, 1977). In contrast to the findings of Schmidt-Kessen and Kendel (1973), the authors reported that increasing ambient room temperature did not affect stages of sleep, at least in the range of 32°C to 39.5°C (Henane et al., 1977). Nonetheless, the one potential inherent limitation of these two earlier studies is they only reveal the effects of higher, not lower, ambient temperature ranges on sleep architecture.

Later research compared the effects of both lower and higher ambient temperatures - 21°C, 24°C, 29°C, 34°, 37°C - on the sleep patterns of a small sample of healthy young male participants (Haskell et al., 1981). Results revealed that Stage 1 sleep increased and Stage 2 sleep decreased in cold temperatures compared to the heat. Furthermore, this study also found that reductions in amounts of SWS and REM sleep were greater in the cold, 20°C and 24°C, as compared to the heat, 34°C and 37°C. Wake after sleep onset (WASO) was also longer in duration in the cold. The authors noted a consistent trend that sleep was more disrupted in the cold than in the heat, at least in short-term exposures. A later study (Muzet, Ehrhart, Candas, Libert, & Vogt, 1983) investigated the effects on sleep architecture of two consecutive nights of sleep in a climactic chamber at 13°C, 16°C, 19°C, 22°C or 25°C with a small sample of healthy young males. In contrast to previous results (Haskell et al., 1981), Muzet et al. (1983) revealed that the total duration of REM sleep along with REM latency, did not significantly differ between conditions.

Other research has also focused on the more prolonged effects of continuous ambient temperature exposures (i.e., three or more consecutive nights) on sleep patterns. The cumulative effects of continuous exposure to heat for five days and nights at an ambient temperature of 35°C was compared to baseline measurements for five days and nights at 20°C in a small sample of healthy males (Libert et al., 1988). Compared to baseline measures at 20°C, sleep patterns were significantly disturbed at 35°C with increasing amounts of wakefulness and a reduction in TST. The mean duration of REM episodes and the cycle length also decreased in the heat. However, there were no changes in sleep architecture from night to night in ambient temperatures of 35°C with the decrease in REM remaining constant. Similarly, the effects of long-term exposure to cold ambient temperatures of 21°C was

studied in a small sample of healthy young men for five consecutive nights (Palca, Walker, & Berger, 1986). Results revealed that WASO increased in ambient temperatures of 21°C, whilst SWS and REM sleep did not change significantly compared to the five night baseline measures at 29°C.

Collectively, this research shows that within a certain range of ambient temperatures referred to as the zone of 'thermoneutrality', quantitative measurements of sleep such as sleep stage latency, time spent in each sleep stage, and the number and duration of awakenings after sleep onset are not modified, and SWS and REM sleep are at their maximum. However, although a 'thermoneutral zone' is always discussed, rarely is a specific ambient temperature defined. This is because thermoneutrality is affected by a number of factors including bedtime clothing, and covering. For example, research allowing bedtime clothing, two cotton sheets and one wool blanket, found that the microclimate established inside a bed varied from only 28.6°C to 30.9°C, whilst ambient temperature fluctuated from 16°C to 25°C (Muzet et al., 1983). This research concluded that 19°C provided the correct ambient temperature to achieve 'thermoneutrality' (Muzet et al., 1983). In a following study, Muzet et al. (1984) observed a similar trend finding that an ambient temperature of 16°C showed little to no disruption to WASO in clothed and covered participants. In contrast, the study by Haskell et al. (1981) reported that sleeping unclothed and uncovered at an ambient temperature of 29°C provided the thermoneutral zone with maximal amounts of SWS and REM sleep with the least amount of WASO. In conclusion although a thermoneutral temperature or zone is always discussed it tends to vary between studies.

2.1.15 Effects on sleep architecture of sleep restriction and ambient temperatures

Research investigating changes to sleep architecture under conditions combining sleep restriction and various ambient temperatures remains sparse, and in the laboratory remains the focus of only a single study (Bach et al., 1994). A small sample of healthy young males underwent sleep restriction to 4 h (from 03:00 h to 07:00 h) for four consecutive nights, with six of the participants exposed to an ambient temperature of 20°C and the other half to 35°C. Results demonstrated that sleep restriction at 20°C was associated with significant reductions in the amount of wakefulness and in Stage 4 sleep latencies, in addition to a significant

increase in the amount of Stage 4 sleep over the four consecutive nights of sleep restriction. The addition of heat to sleep restriction did not result in a significant increase in the amount of Stage 4 sleep as originally found in the temperate 20°C condition. The findings imply that the heat load induced by the increase in ambient temperature to 35°C was associated with a suppressive effect on Stage 4 sleep, where sleep restriction alone results in increased Stage 4 sleep (Belenky et al., 2003; Van Dongen, Maislin, et al., 2003).

2.1.16 Effects on sleep architecture of sleep restriction, physical activity and ambient temperatures

To the author’s knowledge the effects on sleep architecture of combining sleep restriction, physical activity and various ambient temperatures has not yet been studied, either in the laboratory or in the field. One possible exception includes a study by Lieberman, Bathalon, Falco, Kramer, et al. (2005), who examined wrist activity monitoring with a moderate sized sample of young US Army officers during a field exercise conducted in hot-humid weather (19- 31°C). This study showed throughout the 53 h field deployment participants slept a total of 3 h obtained in short naps with average duration of 12 minutes. Since sleep was not objectively monitored during the sustained military operations, the only reports of sleep duration in or relevant to wildland firefighting come from wrist activity monitoring (see Section 2.1.2; Vincent et al., 2016).

2.1.17 Summary

Wildland firefighters are exposed to numerous occupational and environmental stressors including working and sleeping in variations of low and high ambient temperatures in addition to sleep loss (Aisbett et al., 2012; Cater et al., 2007). Wildfires can last for weeks, requiring firefighters to undergo extended work periods, with long day-shifts in the heat and little rest provided between shifts at night (Hunter, 2003; Rodriguez-Marroyo et al., 2012). This often results in shortened sleep opportunities, or a restricted night’s sleep with cumulative sleep loss occurring between consecutive night shifts (Cater et al., 2007; Cuddy et al., 2007). Recent Australian research has shown that firefighters routinely display sleep loss during multi-day fire campaigns (Vincent et al., 2016) with similar reports of sleep loss coming from the US (Gaskill & Ruby, 2004). Furthermore, volunteer firefighters are often

responding to an emergency following their normal work day and thus, fatigue levels may already be elevated before a firefighting duty even commences (Cater et al., 2007). Fires in rural locations may require travel to and from the fireground as well as the need to sleep in temporary accommodation such as tents (McLennan & Birch, 2005; Vincent et al., 2016). All factors that are likely to impact sleep duration and architecture. However, PSG data on Australian wildland firefighters' sleep during multi-day fire campaigns is not available, with EEG measurements of sleep stages remaining unstudied.

Where information is not available for firefighters on the individual and combined effects of ambient temperature, physical activity and sleep restriction on sleep patterns, information from similarly designed laboratory, field and military studies provides some insight. Research examining the effects of acute and continuous high or low ambient temperatures has shown that sleep quality and quantity are optimised when 'thermoneutrality' is achieved. However when the 'thermoneutral zone' is discussed, a specific ambient temperature or range is rarely defined, or temperatures vary between studies (Haskell et al., 1981; Henane et al., 1977; Libert et al., 1988; Muzet et al., 1983; Muzet et al., 1984; Palca et al., 1986; Schmidt-Kessen & Kendel, 1973). While sleep restriction is associated with consistent dose-dependent declines on patterns of sleep architecture (Belenky et al., 2003; Van Dongen, Maislin, et al., 2003), the effects of varying ambient temperature in brief or continuous exposures are unknown.

Importantly, whilst these laboratory, field and military studies describe a number of effects of sleep restriction and ambient temperature on sleep architecture, there are a number of limitations that prevent the generalisation and applicability of their results to the wildland firefighting population and context. Firstly, they were conducted using samples of healthy young participants, or physically fit military personnel of various age ranges. Physically fit individuals tend to demonstrate increased levels of SWS (O'Connor, Breus, & Youngstedt, 1998; Youngstedt, 2005) and may be relatively impervious or protected against the effects of environmental stressors likely to modify sleep patterns or result in sleep loss in young adults (O'Connor et al., 1998; Youngstedt, 2005). Secondly, healthy young norms typically have a routine habitual sleep-wake cycle and are labelled as 'good sleepers'. In contrast, the average age of an Australian volunteer firefighter is closer to 39 years and habitual sleep is likely to be much more varied (McLennan & Birch, 2005). Thirdly, and most importantly, the research protocols employed by previous laboratory studies reveal effects of single and dual stressors

on sleep patterns but never the combination of sleep restriction, physical activity and temperature. Where combinations of environmental and occupational stressors are similar to that of firefighting (for e.g., military operations), direct comparisons of results are problematic due to the periods of initial TSD prevalent in military research (Haslam, 1982; Lieberman, Bathalon, Falco, Kramer, et al., 2005). Thus, whilst these studies reveal a number of findings for sleep on the effects of temperature manipulations, physical activity or sleep restriction, they provide a narrow insight as to the potential outcomes of conditions faced by wildland firefighters.

In summary, the available research shows firefighters experience sleep loss in the field and are at further risk of increased sleep loss during wildfire suppression based on the duration of shifts, timing, and number performed in a row over multiple days during deployments (Cater et al., 2007; Gaskill & Ruby, 2004; Vincent et al., 2016). While research does exist on subjective reports and also objective measurements such as activity monitoring, stages of sleep and sleep architecture during wildfire suppression need to be examined. This type of research is valuable for fire agencies as sleep architecture is known to influence cognitive performance (Belenky et al., 2003; Turek, 1999; Van Dongen, Maislin, et al., 2003) and physical productivity and efficiency on subsequent days (Horne & Moore, 1985; Horne & Reid, 1985; Horne & Staff, 1983; Vincent et al., 2015). Furthermore, if excessive sleep loss is related to declines in firefighter mental or physical performance due to changes in sleep architecture, fire agencies may want to update their existing policy. This could be achieved by changing shift structure to enhance the sleep opportunities of workers, or by incorporating safety controls to mitigate and manage risks associated with sleep loss related fatigue.

2.2 Wildland firefighting, ambient temperature, dehydration and cognitive performance

Wildland fires are known to occur in hot, dry and windy weather conditions associated with temperature ranges between 35°C and 45°C, low humidity and wind speeds of up to 75kmh^{-1} (Cheney, 1976). In these temperatures wildland firefighters are required to perform intermittent physically demanding work for extended periods of time, whilst wearing heat retaining impermeable protective clothing (Aisbett, Phillips, Sargeant, et al., 2007; Aisbett et al., 2012). All of these factors contest body water homeostasis, present a significant challenge to the hydration status of wildland firefighters, and increase health and safety risks (Raines et al., 2015; Raines et al., 2012, 2013). For instance the effects of hydration levels on physiology have been the focus of numerous studies (Coyle, 2004; Sawka et al., 2007; Sharkey, Mulloy, & O'Neill, 1999). Showing that fluid restricted and dehydrated individuals typically experience increased cardiovascular strain (Sharkey et al., 1999), reduced physical work capacity (Coyle, 2004), and heightened core temperatures (Sawka et al., 2007), all of which can eventually lead to exhaustion or collapse and sometimes even death (Sharkey et al., 1999). From a review of five to 10 year injury statistics, from south-eastern Australian fire agencies, Aisbett, Phillips, Sargeant, et al. (2007) revealed heat related injuries to be the third highest leading cause of all fireground related injuries (2-6%). With musculoskeletal strains and sprains (11-41%), and smoke exposure (2-8%) identified as the other major categories (Aisbett, Phillips, Sargeant, et al., 2007).

2.2.1 Dehydration measurement

Hydration was determined by performing a urine specific gravity (U_{sg}) analysis using a portable refractometer (Atago, Japan). Prior to U_{sg} analysis a drop of distilled water was placed on the face of the prism, as standard, to adjust the instrument to 1.000 grams per milliliter ($g \cdot mL^{-1}$). Previous guidelines by the national athletic trainers association reported that a U_{sg} <1.010 specifies well hydrated or euhydrated and corresponds to a +1 to -1 % body weight (B_w) change, a U_{sg} of 1.010-1.020 represents minimal dehydration, and reflects a -1 to -3 % B_w change, whilst a U_{sg} range of 1.021-1.030 represents significant dehydration corresponding to a -3 to -5 % B_w change (Casa et al., 2000). Numerous other studies (Casa, Clarkson, & Roberts, 2005; Oppliger, Magnes, Popowski, & Gisolfi, 2005) have also

collectively identified that a $U_{sg} \geq 1.020$ is associated with significant weight loss and recommend the use of this cut-off as a marker for dehydration. Similarly, numerous other studies (Armstrong et al., 1994; Armstrong et al., 1997; Armstrong et al., 1998; Popowski, Oppliger, Lambert, Johnson, & Gisolfi, 1999; Popowski et al., 2001) have also collectively identified a $U_{sg} < 1.020$ as the value representing euhydration. The results of a recent study by Cheuvront, Ely, Kenefick, and Sawka (2010) also determined a U_{sg} of 1.018 ± 0.006 (mean and standard deviation) be used for euhydration, consistent with a $U_{sg} \leq 1.020$ in previous research. Although, they suggested a U_{sg} value of 1.028 ± 0.006 (range 1.022-1.033) be used for dehydration (Cheuvront et al., 2010).

2.2.2 Wildland firefighting physical work

Australian wildland firefighters are required to perform numerous tasks during work shifts, primarily comprised of manual handling activities (Aisbett, Phillips, Raines, & Nichols, 2007). The physical work demands faced by rural fire service volunteers safeguarding the public from wildfires are well documented (Phillips et al., 2007). The manual labour performed on the fireground during wildland firefighting for tanker-based wildfire suppression primary involves three physically demanding tasks (Phillips et al., 2007). One of the primary activities is carrying fire-tanker hoses to provide water during fire suppression to the site of the fire. Another primary task revolves around the use of hand-tools, for example rake hoes, to produce firebreaks on the fireground, by clearing the earth of combustible fuels such as leaves and shrubbery to curtail the spread of wildfire. Finally, firefighters are required to perform 'blacking out' activities such as clearing and inspecting burnt debris for potential hazards of ignition like fire embers during post-fire suppression operations. Each of the physical tasks used in this thesis have been identified by firefighters as being characteristic of the typical carry and drag activities that comprise the key firefighting tasks frequently performed on the fireground (Lord et al., 2012; Phillips et al., 2012). Additionally, frequency, duration and intensity of each of the tasks was validated by comparing physiological measures recorded in a laboratory simulation against those recorded in the field during wildfire suppression (Lord et al., 2012).

2.2.3 Personal protective clothing and equipment

Physical exercise is a stressor that stimulates increased metabolic activity. When exercising in temperate conditions and normal clothing, heat dissipation mechanisms such as convective cooling allow an individual to maintain thermal homeostasis (Cheung, McLellan, & Tenaglia, 2000). When the body heat generated through exercise is combined with the additional stressor of ambient heat, this further increases the strain on an individual's capacity to maintain balance (Cheung et al., 2000). As wildland firefighters are exposed to radiant heat and flames during suppression activities, personnel are required to wear personal protective clothing (PPC) and equipment (PPE) at all times (Barr et al., 2010). Industry standard PPC and PPE is intended to safeguard the firefighter from environmental hazards and injury and consists of fire retardant pants, gloves, boots, goggles, jacket and a hard-hat, weighing approximately nine kilograms (Son, Bakri, Muraki, & Tochihara, 2014). PPC results in an additional thermal stress to physical exercise and heat, as the limited water permeability of clothing layers hinders the effectiveness of heat dissipation mechanisms such as convective cooling from sweating, increasing dehydration rates (Barr et al., 2010). Previous research focusing on PPC and physical work carried out in hot ambient temperatures demonstrates profuse sweating and dehydration in the absence of sufficient fluid replacement intake (Barr et al., 2010; Sawka et al., 2007).

2.2.4 Structural and wildland firefighting

The cognitive performance of firefighters when dehydrated and performing physical activity in the heat has previously been studied (as discussed in Section 2.2.8; Morley et al., 2012; Zhang et al., 2014). Although the focus of this research (Morley et al., 2012; Zhang et al., 2014) has been on structural as opposed to wildland firefighting and the two occupations are inherently different (Larsen, Snow, & Aisbett, 2015; Larsen, Snow, Vincent, et al., 2015; Larsen, Snow, Williams-Bell, & Aisbett, 2015). One important difference is that structural firefighters are required to wear a self-contained breathing apparatus (SCBA) in addition to structural firefighting PPC that weighs around 19.1 kg (Zhang et al., 2014). Furthermore, by definition structural firefighters are trained to suppress fires posing a danger inside buildings in urban areas or that are a threat to built-up structures in surroundings areas (Larsen, Snow, & Aisbett, 2015; Larsen, Snow, Vincent, et al., 2015; Larsen, Snow, Williams-Bell, et al., 2015; Morley et al., 2012). Where wildland firefighters are trained to suppress bushfires and safeguard surrounding communities, properties and livestock (Aisbett et al., 2012). Wildland

firefighters do protect property such as homes in rural areas, although the fire suppression techniques, and equipment in addition to the types of physical tasks performed on the fireground are not the same as in structural firefighting (Lord et al., 2012; Phillips et al., 2012).

2.2.5 Rural fire industry policies on heat

For the majority of occupations in industrial settings it is possible to set a threshold limit for workers in extremely hot and cold ambient environments. However, in firefighting this is obviously not practical. Instead strategies are provided including safety controls, such as peer monitoring, when temperatures reach a certain threshold (Larsen, Snow, Williams-Bell, et al., 2015). The policy guidelines outlining recommendations and practices for Australian wildland firefighters working in the heat are sparse, and where fire industry policy does exist on extreme temperatures it tends to reflect generic, 'common-sense', recommendations (Larsen, Snow, Williams-Bell, et al., 2015). For example, the Country Fire Authority, Victoria in an operation bulletin for 2012 entitled the 'management of heat stress', stipulated generalised techniques such as "ensure extra supplies of water and electrolyte drinks are available" (CFA, 2012, p. 2). Where possible, policy should reflect empirically verifiable scientifically based evidence and thus further research is required.

2.2.6 Fire industry prescribed fluid intake

In an effort to reduce the potential of dehydration and associated health and safety risks, fire agencies around Australia prescribe target drinking rates for their personnel whilst suppressing wildfires (Raines et al., 2013). Considerable variability exists in the prescribed fluid targets between individual fire agencies, ranging from 500 mL to 3000 mL per hour for each firefighter performing a 12 h fireground shift. Recently Raines et al. (2013) tested adherence to a modest agency-prescribed fluid target with firefighters from Australian and American crews assisting in the 'Black Saturday', February 2009 wildfire suppression and recovery efforts. Firefighters were placed into one of two groups, an *ad libitum* condition or a prescribed target condition of 600 mL of water and 600 mL of electrolytes per hour of the 12 h shift. Ambient temperatures fluctuated over the seven day firefighting period from a minimum of 15.81°C to a maximum of 26.39°C. Regardless of the relatively cool to neutral

ambient temperatures, results revealed that firefighters in the prescribed condition were not able to reach the target volume of 1200 mL per hour although were able to consume enough fluids to leave the fireground hydrated by the end of their shift.

2.2.7 Hydration levels of firefighters during wildfire suppression under Australian conditions

In a similar study by Raines et al. (2012) during the 2009 Victorian bushfire suppression and recovery efforts firefighters were placed into one of two groups: self-selection of the volume, beverage type (water or water plus electrolyte) and timing (i.e., an *ad libitum* condition), or provided a pre-shift bolus of 500 mL of water to be consumed before leaving the station with *ad libitum* consumption thereafter. Temperatures ranged throughout the seven days of firefighting and were considered mild to warm, with an average minimum and maximum of 15.8°C and 26.4°C. Results were consistent with their other research (Raines et al., 2013) in that firefighters typically arrive on shift in a dehydrated state. This has implications for safety and health both on the drive to the shift and on the fireground. However, despite arriving on shift dehydrated, *ad libitum* drinking was sufficient to result in euhydration by the conclusion of the shift. However as it was not feasible to employ in-field hydration measures throughout the shift it is not possible to ascertain exactly when euhydration occurred. The authors concluded firefighters are capable of self-monitoring hydration levels over the course of a 6 h to 13.5 h shift provided that fluid and food choice availability are not limited and achieve euhydration by completion of the shift (Raines et al., 2012, 2013). Although, later research by Raines et al. (2015) showed that in hot conditions with average temperatures of 30.9°C to 32.8°C, firefighters also arrived on shift in a dehydrated state and were unable to regulate their fluid consumption behaviour and work rate to leave the fireground euhydrated.

‘Project Aquarius’ provided the first quantitative information about the water requirements necessary for Australian wildland fire fighters during suppression of experimental bushfires of intensities commonly experienced by hand-tool crews (Hendrie et al., 1997). Their study was based on four crews of seven male firefighters who performed fireline building with hand-tools, primarily rake hoes, in order to create firebreaks, suppressing fifteen experimental bushfires. On another alternative eleven work bouts the teams created firebreaks in the absence of fire. Formal rest breaks were provided every hour for 10 minutes during the bouts

without fire, and periodically for 10-20 minutes when practical during real fire simulations. Firefighters were provided with *ad libitum* access to water throughout the study. Fire building exercises lasted on average for 99 minutes and 135 minutes for non-fire exercises. Results were remarkably consistent. Across four crews over the duration of four summers in two different states, firefighters sweated at an average rate of 1 to 2 kg per hour whilst building firelines, replacing less than half of the fluid lost by water intake. Firefighters dehydrated at an average rate of 0.9% (654 grams [g]) of body mass [B_m] per hour, replacing only 43% of lost fluids during fireline construction, drinking at an average rate of 490 g per hour and replacing only 63% of fluids lost for the entire work day. The resulting sweat rates are comparable to other research into PPC and PPE worn showing firefighters can dehydrate in as little as one hour with sweat rates of up to 2.1 litres (L) whilst performing simulated work tasks in the heat (Rossi, 2003).

2.2.8 Heat stress, personal protective equipment and cognitive performance

To the author's knowledge there only two other studies investigating the effects on cognitive performance of dehydration and exercising in the heat whilst wearing PPC in structural firefighters (Morley et al., 2012; Zhang et al., 2014). The first part of the study by Morley et al. (2012) consisted of 10 healthy young volunteers (age range 25.8 to 18.1 years) performing up to 50 minutes of treadmill exercise in the heat whilst wearing PPC and a SCBA, completing a cognitive test battery pre- and post-exercise. The second part of the study used a similar protocol with 19 healthy males, except cognitive performance was measured pre- and post-exercise and then 60 minutes and 120 minutes post-exercise. Results revealed B_m losses of 1.6% (0.70 kg) in study one and B_m losses of 0.6% (0.4 kg) in study two. Despite these changes, no significant differences were found immediately after exercise on tests of short-term memory, sustained and divided attention, and reaction time (RT). Changes in cognitive performance were revealed on memory only after 60 minutes and 120 minutes post-exercise, in addition to increases in the 10% of slowest RTs 120 minutes post-exercise. The authors concluded that 50 minutes of treadmill exercise in PPC and a SCBA produced near maximal physiologic strain however cognitive performance was not affected until at least one hour following exercise. The authors acknowledged one of the potential limitations of the research was that the exercise bout did not incorporate the use of upper body activity that is required

for fighting structural fires and that this could potentially result in greater cardiovascular stress during exercise.

The other study by Zhang et al. (2014) examined the effects on cognitive performance of three counterbalanced conditions of caffeine, menthol lozenges, or a placebo on 10 healthy young participants (mean age 24 y) during simulated structural firefighting conducted in the heat (35°C) whilst wearing PPE and a SCBA (19.1 kg). Results revealed that regardless of B_w losses greater than 3% in all conditions, no significant differences were found between either the conditions or between pre to post measures within conditions, on cognitive tasks of simple RT, short-term memory, and retrieval memory. The authors acknowledged that one reason for the insignificant results was due to the inexperience of normal participants being less accustomed to the structural firefighting scenario of extreme heat, PPC, and profuse sweating. Furthermore, the 'simulated firefighting' consisted of a 16 minute treadmill walking exercise followed by a 16 minute stepping exercise. So while walking may certainly be a component of wildfire physical tasks, encountering 20 minutes of steps in wildfire terrain would be unlikely.

2.2.9 Effect on cognitive performance of dehydration from physical activity and heat

Early comprehensive landmark studies assessing the effects of dehydration on cognitive performance were first conducted by Sharma and colleagues during the 1980s in a series of experiments using a combination of high external temperatures and aerobic exercise to induce dehydration (Gopinathan et al., 1988; Sharma, Sridharan, Pichan, & Panwar, 1986). Eight heat acclimatised young males were dehydrated to 1%, 2%, and 3% of their B_w (Sharma et al., 1986). Participants performed bouts of step-up, step-down activity at 15 steps per minute on a 38 cm high stool in a climactic chamber under either hot-dry (45°C temperature dry bulb [T_{db}]) or hot-humid (39°C T_{db}) conditions. Results demonstrated consistent dose-response declines in the majority of cognitive tests administered. For the symbol substitution test significant effects were found at the 3% level of dehydration for both conditions. For the hand-eye co-ordination test significant effects were observed at the 1% level of dehydration in the hot-dry condition only, then both conditions at 2% and 3%. The authors concluded that dehydration at 2% as well as 3% B_w results in a significant decline in mental efficiency.

In a follow-up study by the same research group, 11 healthy young heat acclimatised soldiers (age range 20 - 25 y) replicated the step-up, step-down exercise (15 steps min^{-1}, 38-cm high stool) in a climatic chamber at a temperature of 45°C (T_{db}), with concurrent water restriction until participants were dehydrated to 1%, 2%, 3%, and 4% of their B_w (Gopinathan et al., 1988). There was also a euhydrated control condition with heat and exercise exposure, in addition to a thermoneutral, no exercise control condition. Results demonstrated that tests of short term memory, serial addition and trail making (i.e., speed and accuracy) deteriorated proportionately with the level of dehydration becoming highly significant at the 2% level of dehydration with cognitive performance steadily declining at 3% and 4% levels. The authors concluded that there was a decline on complex mental tasks requiring a high level of attention from dehydration losses of 2% B_w or more. The authors posited that alterations in mental performance were mostly attributable to heat-induced dehydration. They further suggested that cognitive performance impairments shown in previous heat research that did not include hydration measures, have attributed the decline to the stressor of heat, whereas the effect being quantified may have actually resulted from 'voluntary dehydration' (i.e., inadequate water intake) during heat exposures.

However, in all of the previously described studies dehydration levels were induced by exposure to heat combined with physical exercise, which distinctively differs on the physiological pathway responses that are activated, as compared to dehydration induced passively by heat (i.e., hyperthermia), or by exercise alone. The activation of alternate physiological pathways induced by varying dehydration methods may also differentially affect the various brain regions and neurotransmitter systems underpinning each type of cognitive function (Cian et al., 2000). For example, depending on the type of dehydration, different physiological effects are observed, for example variations in water distribution, as well as variations in renal response and in the involvement of hormones in the hydromineral metabolism (Cian et al., 2000). Earlier studies (Gopinathan et al., 1988; Sharma et al., 1983; Sharma et al., 1986) also present an experimental design confound due to combining both heat exposure and exercise as is it presumes that both heat and exercise will have equivalent or similar effects on hydration levels and resulting cognitive performance, which they may not.

2.2.10 Effect on cognitive performance of dehydration from physical activity or passive heat

To overcome previous limitations in the literature where studies combined both heat exposure and exercise, Cian and colleagues (2001; 2000) studied the effects of dehydration induced via heat or exercise in isolation on cognitive performance. Eight healthy endurance trained runners (mean age 27.4 y) un-acclimated to heat were dehydrated to 2.8% of B_m via exercise, or passively by heated ambient temperatures, or euhydrated or hyperhydrated, in a cross-over design with participants receiving all conditions (Cian et al., 2000). Heat acclimation is generally defined by the process of adaptation measured by the cessation of physiological responses that occur from heat stress, for example, such as cessation of sweating, and a return in heart rate to pre-heat stress, or baseline levels (Li et al., 2018). Cognitive measures of perceptive discrimination, psycho-motor skills, and short-term memory, all displayed deficits in the dehydration conditions 30 minutes post hydration manipulation. Further, an additional arm crank exercise was also implemented 15 minutes post hydration manipulation with cognitive performance in the dehydration conditions demonstrating a near return to euhydration values with the exception of tracking performance. This study demonstrated that dehydration achieved via exercise or heat stress has similar detrimental effects on cognitive performance (Cian et al., 2000). Furthermore, this study also showed that the effects of dehydration could be rapidly reversed following a bout of exercise 2 hours post dehydration.

In a follow-up study Cian et al. (2001) dehydrated seven healthy endurance trained runners un-acclimated to the heat (mean age 25 y) to 2.8% of their B_m. Each participant was subjected to five experimental sessions, with two trials of dehydration by passive exposure to heat (45-50°C; with and without fluid replacement) and two trials of dehydration by treadmill exercise (T_{db} 25-26°C) with a control session (2 h semi-recumbent position, thermoneutral environment 25°C T_{db}). Cognitive measures were administered 30 minutes post hydration manipulation and demonstrated similar declines in measures of perceptual discrimination and short-term memory regardless of the method of dehydration. Additionally, cognitive measures administered 3 h and 30 minutes post-hydration manipulation revealed the impairing effect of dehydration on cognitive performance to dissipate with no marked differences existing between the dehydration and control conditions. Similar to Gopinathan et al. (1988), Cian and colleagues suggested that dehydration stress diverting attention may

impact more heavily on tasks that are cognitively effortful and require a greater allocation of attentional resources, as opposed to tasks that are more automated and require less cognitive resources (Cian et al., 2001; Cian et al., 2000).

Similarly, the effect on cognitive performance of mild dehydration from exercise without inducing hyperthermia (i.e., dehydration resulting from heat) was investigated more recently (Ganio et al., 2011). Twenty-six healthy young males males completed three randomised, single-blind, repeated measures trials consisting of exercise induced dehydration on a treadmill (in temperate conditions of 27.7°C) with or without a diuretic, or a euhydrated trial. Results demonstrated that dehydration in a mild range of 1-2 % B_m loss, with or without a diuretic, degraded cognitive performance by increasing the number of errors on visual vigilance and decreasing response latency in visual working memory. It was concluded that mild dehydration without hyperthermia produces adverse changes in cognitive aspects of vigilance and memory. In a follow-up study, showing converse results, the effects of mild dehydration without hyperthermia were investigated on the cognitive performance of a large sample of young women (Armstrong et al., 2012). Twenty-five females (mean age 23 y) were dehydrated to 1.36% of B_m via exercise (in temperate conditions of 26.8°C to 28.4°C) with or without a diuretic or remained euhydrated. Mild dehydration had no effect on a range of cognitive tests including cognitive testing at rest, scanning visual vigilance, psychomotor vigilance task (PVT), grammatical reasoning, repeated acquisition, matching-to-sample, and four-choice visual reaction time. The authors concluded that mild dehydration without hyperthermia does not substantially alter key aspects of cognitive performance in healthy young women.

2.2.11 Effects on cognitive performance of dehydration in colder temperatures.

Other research has focused on the combined effects of dehydration in cold temperatures as opposed to previous research in heat (Adam et al., 2008). Eight healthy soldiers (two females, six males; mean age 24 y) completed four trials of cycling for 60 minutes at 60% of VO_{2max} in either a cold (2°C) or temperate condition (20°C) with pre- and post-cognitive testing. Prior to each trial participants were exposed to 3 h of passive heat stress (45°C) with or without fluid replacement followed by prolonged recovery. Results revealed no effect of

dehydration in either temperature on pre- to post-scores on military tasks of sedentary duty/marksmanship and visual vigilance (hits, false alarms and RT). It was concluded moderate dehydration (-3% B_m) during cold or temperate air exposure does not degrade militarily-relevant task performance, with cold exposure alone producing equivocal effects. Nonetheless, the potential for aerobic exercise alone to have improved some aspects of military performance was acknowledged.

2.2.12 Effect on cognitive performance of dehydration in experimental laboratory protocols

Research has also focused on whether mental performance is slowly affected by progressive moderate dehydration induced over a 24 h period, as opposed to acutely (i.e., 1 h to 3 h of rigorous exercise protocols or intense heat exposures; Szinnai, Schachinger, Arnaud, Linder, & Keller, 2005). Sixteen healthy young volunteers (eight females, eight males, age range 20-34 y) completed tests of cognitive performance following a 24 h period of fluid restriction or during normal fluid consumption in a randomised cross-over design, with a seven day interval between conditions. Results revealed water deprivation resulted in a 2.6% decline in B_w however cognitive-motor and neuropsychological tests did not differ between the water deprivation and control conditions. It was concluded that cognitive functioning is stable on measures including a choice RT task and the Stroop word colour task, in either young male or female adults to a moderate dehydration level of 2.6% of B_w.

Previous research on exercise induced dehydration had focused on cognitive performance only in the post-exercise phase, and not throughout the exercise. Thus, Grego and colleagues (2005) assessed the cognitive performance of eight healthy young men every 20 minutes during a three hour cycling protocol (approximately 60% of VO_{2max}) and five minutes post-exercise termination, in two conditions, of fluid or no fluid. Results showed regardless of B_m losses of 2.2% and 4.1%, in the fluid and no fluid conditions respectively, cognitive performance on map recognition and a critical flicker fusion task did not vary as a function of hydration status. The authors posited that dehydration may exert less of an influence on cognitive performance during and immediately following exercise, than after a delay. Alternatively, it may be that the cognitive tests used by Grego et al. (2005) were not

sufficiently sensitive to detect minor changes in cognitive functioning induced by dehydration.

Similarly, the effect on cognitive performance of dehydration induced by varying durations of exercise and fluid restriction on cognitive performance has been tested (Tomporowski, Beasman, Ganio, & Cureton, 2007). Eleven competitive male cyclists (mean age 26 y) cycled in a climate chamber (30°C) at 60% of VO_{2max} for either 15 minutes, 60 minutes or 120 minutes without fluid replacement or completed a control condition of 120 minutes exercise with fluid replacement. Results revealed B_w losses of 1.27%, 2.27%, 3.67% and 0.69% for the 15 minute, 60 minute, or 120 minute exercise conditions without fluid replacement and the control condition respectively. Cognitive performance on pre- and post-tests of short-term memory did not significantly differ between conditions regardless of dehydration status. Their results revealed that short-term memory performance improved following exercise in all conditions. In addition, cognitive performance on an executive function task was adversely affected as a function of hydration status with speed on the task increasing albeit at the expense of increased errors on choice-responses, reporting a speed-accuracy trade-off. Interestingly, their findings noted that participants' choice-response errors depended on the type of processing involved in decision making. That is, increased errors were found during trials requiring a shift in decision-making rules, for example, switching from numeric to alphabetic categorical based decisions, rather than during trials when no switching was required. The authors concluded that the adverse impact of exercise-induced dehydration is greater on tasks that require more cognitive effort and depend on attentional processes rather than simple repetitive tasks.

Other research has focused on the effects of fluid restriction, heat stress and exercise on choice reaction time (CRT; Serwah & Marino, 2006a). Eight young males (mean age 24.5 y) cycled at approximately 70% of peak power in warm, humid conditions (31°C) for 90 minutes or until exhaustion in three conditions of either 100% fluid loss replacement, 50% fluid loss replacement or no fluid intake. A choice reaction time task was conducted pre- and post-cycling and also 20 minutes and 30 minutes during cycling. Results revealed B_m losses of 0.2%, 1%, and 1.7% in the 100% fluid loss replacement, 50% fluid loss replacement and no fluid intake conditions respectively, however cognitive performance on the CRT did not significantly differ between the three conditions. Furthermore, there were no main effects on CRT of either hydration levels or the stage/duration of exercise during which CRT was

performed. It was concluded that hydration may not be the principal factor producing differences in mental processing outcomes, but rather the exercise itself may be the determining factor. For example, improvements in RT have been demonstrated immediately following exercise durations greater than 20 minutes (Chmura, Krysztofiak, Ziemba, Nazar, & Kaciuba-Uscilko, 1998; Collardeau, Brisswalter, & Audiffren, 2001; Collardeau, Brisswalter, Vercruyssen, Audiffren, & Goubault, 2001). Hence, the deleterious effect of dehydration may be counterbalanced by the increase in arousal resulting from exercise.

2.2.13 Effect on cognitive performance of dehydration in military operations

In the majority of studies mentioned, dehydration losses were studied from a single bout of exercise or heat exposure. However the effects of dehydration losses from repeated sessions over a day could enhance declines in cognitive performance as shown in sustained military operations (Lieberman, Bathalon, Falco, Kramer, et al., 2005). Research conducted with 31 elite U.S. Army officers (mean age 31.6 y) evaluated cognitive performance and hydration measures throughout a sustained operations training exercise for 53 h in the heat (maximum ambient temperature of 31°C and minimum of 19°C). Results revealed dehydration losses of 4% of B_w (losing 4.1 ± 0.2 kg) were associated with highly significant ($p<.001$) performance decrements on cognitive measures of vigilance, reaction time, attention, memory, and reasoning. The authors concluded that even well-trained leaders exhibit significant degradation in cognitive performance when exposed to severe combat-like stressors of sleep loss, heat, and dehydration (Lieberman, Bathalon, Falco, Kramer, et al., 2005). However, the periods of total sleep loss involved in military operations are not consistent with the type of sleep loss experienced during wildland firefighting, which tends to be gradual sleep loss accrued over a consecutive number of nights (Cater et al., 2007; Vincent et al., 2016).

2.2.14 Effect on cognitive performance of dehydration in older ages

The effects on cognitive performance of dehydration have also been studied in an elderly sample consisting of 28 participants (22 females, six males) with an age range of 50 years to 82 years (mean age 63.7 y) (Suhr, Hall, Patterson, & Niinistö, 2004). Participants were allocated to one of two conditions and instructed to either abstain from drinking, or to drink

normally, the night before the study. Hydration status was significantly related to cognitive performance with dehydrated participants performing worse on measures of psychomotor processing speed and on attention and memory tasks. It was concluded that dehydration as a contributor to declining cognitive performance in older adults may be present with even only a relatively mild level of dehydration (Suhr, Hall, Patterson, & Niinistö, 2004).

2.2.15 Validity and generalisability limitations of sport-science literature for wildland firefighting: A summary

Whilst these studies provide insight into the effect of different dehydration levels on cognitive functioning, the majority were conducted using samples of athletes, healthy young physically fit participants, industrial, or military personnel. While these types of study designs have some value they have limited generalisability to wildland firefighting. For example, the majority of studies had samples with a mean age range between 20-25 y, while a 2005 survey of Country Fire Authority first year volunteers revealed a mean age of 39.2 y (standard deviation [SD] = 14.36 y; McLennan & Birch, 2005). Moreover, volunteer wildland firefighters are not comparable to physically fit, healthy young participants, athletes, or soldiers in terms of body mass index (BMI). A normal BMI range is within 18.5 to 24.9 kg/m^2, although recent studies of wildland firefighters report BMI means (± SD) of 27.3 ± 4.7 kg/m^2 (Raines et al., 2012). Furthermore, field studies monitor the effects of temperatures experienced within the operating environment. Their purpose was not to manipulate temperature and examine the effects on hydration and cognitive performance. Also, field research inherently involves fluctuations in extraneous variables that make it difficult to isolate the specific effect of independent variables.

Further, while rigorously controlled laboratory experiments overcome the inherent limitations of field studies, the exercise protocols are not typical of firefighting. The range of exercises, fitness requirements, work-to-rest ratios, intensities, durations and types of physical exercises used in these studies usually consist of acute or single exercise bouts, for example 15 minutes of treadmill walking, or one-off maximal physical efforts. Further, firefighting work is primarily self-paced with the exception of external environmental influences dictating the pace of firefighting, such as the severity of the fire itself (Budd et al., 1997).

2.2.16 Gaps in current research on heat, temperature and dehydration with recommendations for future research

As temperature increases around the world, a warmer global climate will be associated with more frequent wildfires (Hennessy et al., 2005; Liu et al., 2010; Teague et al., 2010). This in turn will place an increasing strain on the demands of wildland firefighters. Optimising firefighter cognitive productivity and efficiency under environmental and occupational stressors such as heat and dehydration should be a research priority for fire agencies. To date no research exists on hydration and cognitive performance for wildland firefighters under different ambient temperatures.

Where studies have focused on wildland firefighters the bulk of this research is directed towards physiological effects but rarely cognitive functioning (Cuddy, Ham, Harger, Slivka, & Ruby, 2008; Hendrie et al., 1997; Raines et al., 2015; Raines et al., 2012, 2013; Ruby, Schoeller, Sharkey, Burks, & Tysk, 2003). Collectively though this research highlights that ambient temperature and physical firefighting tasks pose a significant challenge to the hydration status of wildland firefighters in hotter and also in somewhat milder temperatures.

Further, conflicting findings exist in relation to the effects on cognitive performance of exercise and hydration in mild (i.e., 18-20°C) temperatures (Adam et al., 2008; Cian et al., 2001; Cian et al., 2000; Ganio et al., 2011; Grego et al., 2005). Similarly, research on the effects on cognitive performance of exercise, heat, and dehydration combined have reported contrasting findings from a handful of studies (Gopinathan et al., 1988; Serwah & Marino, 2006; Sharma et al., 1983; Tomporowski et al., 2007). Importantly, all of this research has relied primarily on three experimental methods to induce dehydration: passive dehydration (for example, fluid restriction), heat exposure (i.e., hyperthermia) and exercise, or a combination of exercise and heat, or diuretics. However, presently there is no existing laboratory or field research utilising a protocol comparing both temperate and hot variations in external temperatures with physical activity and hydration to determine the effects on cognitive performance. Moreover, laboratory studies focusing solely on passive heat induced dehydration have little relevance for wildland firefighting, as intermittent physical work is a requirement of the duty. Hence it would be more likely a firefighter would have resulting

dehydration levels due to either physical exercise alone or physical exercise in heated ambient environments.

It is important for fire agencies to know if mental functioning declines with dehydration, potentially placing individuals at increased risk of error and incident when working in both hot weather conditions and in cooler temperatures. For ecological validity these effects are usually studied in the field. However as temperature, wind, and the severity of the emergency situation are all highly variable it is more difficult to use field data to isolate the effect of temperature with physical activity on cognitive performance. Furthermore it is difficult to test firefighters in an emergency setting without interrupting or delaying the ongoing fire suppression or disaster relief operations (Aisbett, Phillips, Sargeant, et al., 2007).

The next step of research is to examine actual firefighters in the laboratory on a reliable cognitive test battery known to be sensitive to the effects of dehydration in addition to a well-validated battery of physical firefighting tasks that simulate fireground work (Lord et al., 2012; Phillips et al., 2012; Phillips et al., 2011). This will provide valuable information on the effect on cognitive performance of hydration during wildfire suppression shifts in both ambient heat and temperate conditions

2.3 Wildland firefighting, sleep restriction, physical activity, temperature and cognitive performance

2.3.1 Firefighting and cognitive performance

There is only a handful of studies on structural firefighting and cognitive performance conducted by the same cohort of researchers (Smith, Manning, et al., 2001; Smith & Petruzzello, 1998), that are independent of dehydration body mass losses in the heat (Morley et al., 2012; Rayson et al., 2005; Zhang et al., 2014). The first study by Smith and Petruzzello (1998) examined 10 career firefighters during three types of structural firefighting drills in a live-fire training facility (temperatures range 53.6-78.7°C). Two different configurations of firefighting gear were used and the outcome measure was a continuous performance test (CPT). Firefighting activities consisted of dragging a dummy hose around an obstacle course, carrying a weighted bucket up and down stairs, fire extinguishing, hose hoisting and lowering from heights, and wood chopping. Results revealed no significant effect from pre- to post-measures of either the firefighting equipment configurations, types of live firefighting drills, or their interaction on speed of responding (i.e., RT) and accuracy of responding (i.e., number of errors) on the CPT. In the second study, seven recruit firefighters performed the same three standardised trials of firefighting tasks in temperatures of 46.6-60.5°C (Smith, Manning, et al., 2001). Consistent with the first study, results revealed no significant effect from pre- to post-measures from the three types of live firefighting drills on RT and the number of errors on the CPT. Whilst this research demonstrates that cognitive deterioration due to heat stress alone was negligible, the effects of sleep loss alone, or in combination with heat, on cognitive functioning remain to be determined in the firefighting population. Where other research has investigated changes in cognitive performance during firefighting simulations the focus has been on activities such as ‘smoke-diving’, which similarly to structural firefighting have little to no relevance for Australian wildland firefighters (Kivimäki & Lusa, 1994).

2.3.2 Effects on cognitive performance of sleep loss

2.3.2.1 Sleep loss and psychomotor vigilance

The effects of sleep restriction on cognitive performance are well established with two seminal studies in this millennium reporting similar effects from chronic sleep restriction

protocols (i.e., seven or more consecutive nights in a row). In the study by Belenky et al. (2003), 60 healthy male (age range 24-62 y) and female volunteers (age range 24-55 y) were assigned sleep opportunities of 3 h, 5 h, 7 h, or 9 h daily TIB for seven days of sleep restriction. Results demonstrated for PVT measures of reciprocal reaction time (RRT), lapses (RTs > 500 ms) and the fastest 10% of all responses that the seven days of sleep restriction degraded performance in a sleep-dose dependent pattern. Cognitive performance in the 5 h and 7 h TIB groups initially declined in response to sleep restriction, then after a few days performance plateaued stabilising at lower than baseline levels. In the 3 h TIB group performance continuously declined across days of sleep restriction without any indication of performance stabilising. As expected the 9 h TIB group displayed no effect on performance over the seven day experimental period. The authors concluded based on their findings that the minimum duration of sleep required to produce stable daytime performance, although at a reduced level, is approximately 4 h sleep per night. Although this research did not investigate whether sleep at different times of day, apart from at night, has the same effect on daytime performance. Another large-scale study randomised 48 healthy male and female adults to either 4 h, 6 h, or 8 h sleep opportunities for 14 days, or to 0 h TSD for three nights (Van Dongen, Maislin, et al., 2003). Chronic restriction of sleep to 4 h or 6 h for 14 days in a row resulted in cumulative performance deficits in PVT, digit symbol substitution and serial addition and subtraction performance, relative to the 8 h sleep opportunity. The results of these two studies (Belenky et al., 2003; Van Dongen, Maislin, et al., 2003) are also consistent with the findings of an earlier major sleep restriction study showing performance impairments on PVT lapses, and the fastest and slowest 10% of response times following seven nights of sleep restriction to 4.98 h (Dinges et al., 1997).

Additionally, five recent studies all employing shorter or acute (i.e., five or less consecutive nights in a row) sleep restriction protocols of 4 h sleep for five nights have demonstrated performance impairments on lapses for a 10 minute simple RT task and virtually all measures of the PVT, including mean RT, mean RRT, lapses, fastest 10% RT, and slowest 10% RRT (Banks, Van Dongen, Maislin, & Dinges, 2010; Basner & Dinges, 2011; Goel, Abe, Braun, & Dinges, 2014; Haavisto et al., 2010; Philip et al., 2012). Even lesser durations of three consecutive nights of sleep restriction to 4 h have shown consistent increases on PVT mean RT and lapses in a homogenous participant sample of women (Stenuit & Kerkhofs, 2005). Moreover, other research using acute sleep restriction protocols of only two nights to either 4 h or 4.8 h, reported performance declines on PVT median RT, mean RT and lapses (Drake et

al., 2001; Swann, Yelland, Redman, & Rajaratnam, 2006). Only one study to the author's knowledge has reported no effect following two nights of sleep restriction to either 3 h or 5 h on median RT, mean fastest 10% RT and lapses (Rupp, Arnedt, Acebo, & Carskadon, 2004). Although in contrast, two recent studies have shown sleep restriction to 4 h for only a single night (also known as partial sleep deprivation) resulted in impairments on PVT mean RT, SD of RT, lapses, and the fastest and slowest 10% RT (Innes, Poudel, & Jones, 2013; Schwarz et al., 2013). Collectively, these studies inform us that there are slight differences in cognitive performance on the PVT even between one and two or even up to five or more nights of sleep restriction.

2.3.2.2 Sleep loss and inhibitory control/response inhibition

While it is widely accepted that sleep loss affects performance on tasks requiring automatic responding or sustained vigilance such as the 'Psychomotor Vigilance Task', few empirical studies have assessed the role of sleep restriction on higher-order or executive cognitive functions such as response inhibition or inhibitory control (Rossa, Smith, Allan, & Sullivan, 2014). Response inhibition is the executive cognitive function necessary to prevent or withhold the initiation of an automatic pre-potent response when that reaction is not required (Drummond et al., 2006). The Stroop task is a test involving the executive function of inhibitory control as correct responses on the task require the inhibition of a pre-potent response. For incongruent or non-matching Stroop trials, the font colour of the written word does not match the text, for example the word "RED" is coloured in blue font. This requires participants to respond by naming the font colour by inhibiting the pre-potent automatic tendency to name what is written (Dixit & Mittal, 2015). The assumption for Stroop inhibitory control is that naming the colour of the word requires more cognitive effort in attention, as opposed to reading the word, which is an automatic process (Dixit & Mittal, 2015). Response inhibition is also measured using a Go/Nogo task, which requires responses to "Go" stimuli reflecting automatic vigilance and motor acceleration controlled by the motor cortex. Withholding a response to "Nogo" stimuli indexes response inhibition as presided over by the central executive system in the prefrontal cortex (Honma, Yoshiike, Ikeda, & Kuriyama, 2015).

2.3.2.3 Sleep restriction and the Stroop task

There is very little consensus on the effects of sleep restriction on Stroop and Go/Nogo task performance. For instance one study showed that sleep restriction to 4 h for three nights in a

sample of younger and older women resulted in an increase in total response times and the total number of errors on the Stroop interference trial (i.e., the non-matching colour-word trial minus the neutral trial). This impairment in Stroop performance was shown by the third day of sleep restriction compared to after the recovery night which was taken as the baseline measurement. The authors concluded the Stroop task was ‘really’ sensitive to sleep restriction and that sleep restricted subjects were unable to resist the instinctive automatism to read what was written, reflecting some form of impulsiveness (Stenuit & Kerkhofs, 2008). In contrast, another study on the comparative utility of cognitive measures assessing the impacts of sleep restriction (seven nights of 9 h, 7 h, 5 h or 3 h sleep) reported no significant effect sizes on Stroop non-matching colour-words for response times or percentage correct. The authors suggested the task was not overly sensitive to sleep restriction (Balkin et al., 2004).

2.3.2.4 Poor/Disrupted sleep and the Stroop task

Other studies on poor self-rated sleep quality provide support for the idea that sleep loss has little effect on Stroop task performance often reporting null effects on Stroop response times and number correct on matching and non-matching colour-words in addition to Stroop interference (Barnett & Cooper, 2008; Kim, Kim, Park, Choi, & Lee, 2011; Nebes, Buysse, Halligan, Houck, & Monk, 2009; Okamura et al., 2010). For example, residents and interns placed into one of three sleep groups of less than 4 h, 4 h to 6 h, or more than 6 h sleep for two weeks did not show any significant differences between the groups for response times to non-matching colour-words (Kim et al., 2011). This led the authors to conclude that given the skilled nature of residents and interns it is possible for the brain to adapt to chronic sleep restriction to stabilise performance. These results are also consistent with another study using a month long survey showing no significant differences between sleep groups of less than 5 h or 6 h to 8 h per night on the number of responses and response times to matching and non-matching colour-word stimuli (Okamura et al., 2010).

2.3.2.5 Complete sleep loss and the Stroop task

Research focussed on increasing homeostatic sleep pressure from total sleep deprivation has reported null (Binks, Waters, & Hurry, 1999; Jackson, Croft, Kennedy, Owens, & Howard, 2013; Pace-Schott et al., 2009), mixed (Dixit & Mittal, 2015), positive (Sagaspe et al., 2006) and negative (Cain et al., 2011) results on Stroop performance. For example, one study showed in 19 middle-aged professional drivers that Stroop response times to matching and non-matching colour-words did not significantly change after a normal night’s sleep

compared to after 27 h of TSD (Jackson et al., 2013). Similarly, another TSD study compared sleep deprived participants after 35 to 39 h of sleep loss revealing no decrements on Stroop interference and the number correct on non-matching colour-words when compared to non-sleep deprived controls (Pace-Schott et al., 2009). Interestingly, faster response times to non-matching colour-words have also been reported following total sleep loss compared to baseline measures, while the percentage of errors remained unaffected (Sagaspe et al., 2006). The authors explained their results in terms of a practice effect suggesting participants developed a reading suppression response potentially masking the effect of sleep loss. In contrast, a more recent TSD study showed a slowing of response times with a concurrent increase in the percentage of errors following one night of complete sleep loss (Cain et al., 2011). However this study (Cain et al., 2011) administered a computerised single-trial version of the Stroop over the classical card version of the task as used by Sagaspe et al. (2006). This is an important distinction as the single-trial version allows the response time to each individual trial to be taken into account and includes response times for correct responses only, whereas the classical version includes an average response time over both correct and incorrect responses (MacLeod, 1991).

Other applied research during a 105-day space flight mission has investigated the inhibitory control component of the Stroop task (calculated as the median response time on non-matching colour-words minus the median response time on matching colour-word pairs). This research showed that Stroop task performance did not vary significantly across the workdays for crewmembers or mission controllers averaging 7 h and 5 h sleep respectively, prior to an extended night workshift (24 h; Barger et al., 2014). Although, during the extended 24 h nightshift there was a significant decrement in the inhibitory control component of executive functioning for mission controllers. These results suggest a significant amount of sleep loss may be detrimental to Stroop inhibitory control.

2.3.2.6 Partial sleep deprivation and the Stroop task

There is some evidence that partial sleep deprivation (i.e., one single night of sleep loss) may affect the Stroop task (Jarraya, Jarraya, Chtourou, Souissi, & Chamari, 2013; Jarraya, Jarraya, Chtourou, & Souissi, 2014; Tassi et al., 2006). Research has shown after a single night of partial sleep deprivation to 2 h that during first half hour of a Stroop task completed on awakening, participants had a slow reaction time while the percentage of errors remained constant (Tassi et al., 2006). However, during the second half hour participants adopted a

new strategy and response times became faster, albeit with an increase in the percentage of errors. In contrast to the 2 h partial sleep deprivation group, there was no speed-accuracy trade-off found in the 8 h control group (Tassi et al., 2006). The authors concluded that the accumulation of fatigue during the second part of the morning led to a change in strategy for the sleep deprived subjects where they favoured speed at the expense of accuracy. Furthermore, two studies by Jarraya and colleagues (2013; 2014) showed that partial sleep deprivation for a single night resulted in impaired performance on the Stroop task. Collectively, their findings showed that either 4 h or 5 h of sleep loss for one night decreased the number of correct responses to matching and non-matching colour-words relative to a baseline night's sleep of 8 h to 9 h as a control condition. Additionally, their results also showed time-of-day effects with Stroop accuracy declining from the morning to the evening sessions in both the partial sleep deprivation and control conditions.

2.3.2.6 Sleep restriction and the Go/Nogo task

Similar to the Stroop task, sleep restriction studies focusing on the Go/Nogo task have not yet reached a consensus with mixed results reported in two recent sleep restriction studies (Rossa et al., 2014; Stenuit & Kerkhofs, 2008; Swann et al., 2006). One sleep loss study employing the Go/Nogo task showed that female participants undergoing sleep restriction to 4 h for three consecutive nights demonstrated a significant delay in total response times between baseline measures and sleep restriction night two. In contrast, another study reported the mean number of false alarms (i.e., incorrect responses to Nogo trials) for fearful faces was not affected, with a similar rate of emotional Nogo false-alarms following a single night of partial sleep deprivation to 3 h compared to a habitual night's duration of sleep (6.7 h; Rossa et al., 2014).

2.3.2.7 Poor/Disrupted sleep and the Go/Nogo task

Research has also focussed on the effects of poor and disrupted sleep on the Go/Nogo task (Breimhorst, Falkenstein, Marks, & Griefahn, 2008; Nota, Schubert, & Coles, 2015; Schapkin, Falkenstein, Marks, & Griefahn, 2006a, 2006b). Notably, performance on the Go/Nogo task is not always affected following a single night of poor self-rated sleep. Three of four studies have reported no change in behavioural outcome measures of mean RT on Go stimuli, mean number of missed Go stimuli, and the mean number of false alarms for Nogo stimuli, in response to self-rated sleep quality measures (good vs. poor) after a single night's sleep (Breimhorst et al., 2008), or after noise-induced sleep disturbances (Schapkin et al., 2006a, 2006b). Collectively, these studies could suggest Go/Nogo task performance may not be affected by disrupted sleep or associated with poor self-rated sleep quality (Breimhorst et

al., 2008; Schapkin et al., 2006a, 2006b). Although, one more recent study (Nota et al., 2015) provides partial support for the notion that poor sleep leads to performance decrements. This research showed that inadequate or poor sleep duration is associated with increased errors on Nogo trials in individuals with heightened levels of obsessive compulsive symptomatology or repetitive negative thoughts (Nota et al., 2015).

2.3.2.8 Complete sleep loss and the Go/Nogo task

The suggestion that sleep loss may influence Go/Nogo performance has also been reported with delayed RTs in the morning following a single night of complete sleep loss in comparison to a normal night's sleep (Bougard, Moussay, Espié, & Davenne, 2015). With few exceptions (Manly, Robertson, Galloway, & Hawkins, 1999) studies that have manipulated sleep durations with total sleep deprivation and constant routine protocols have revealed remarkably consistent results (Almklov, Drummond, Orff, & Alhassoon, 2015; Chuah, Venkatraman, Dinges, & Chee, 2006; Drummond et al., 2006; Sagaspe et al., 2012). These studies provide support for the notion that increased homeostatic sleep pressure from sleep restriction has the potential to deregulate the cognitive processes underlying inhibitory response control on the Go/Nogo task (Rossa et al. 2013). For example, one major study showed Go/Nogo task performance impairments in hit rate (i.e., correct Go responses), hit RTs (i.e., Go response times), and false alarms following 55.75 h, 31.75 h, and 23 h, of complete sleep loss, respectively (Drummond et al., 2006). Similarly, another study reported deficits on the percentage correct for both Go and Nogo stimuli following 24 h of TSD (Chuah et al., 2006). Furthermore, a study of healthy younger and older males showed that performance on Go RTs for correct responses, percentage of missed Go stimuli and false alarms all deteriorated with 40 h of extended wakefulness under a constant routine protocol (Sagaspe et al., 2012). Finally, another study on both younger and older male and female adults over 36 h of TSD found performance significantly deteriorated on measures of RT for correct responses to Go stimuli and the proportion of false alarms (Almklov et al., 2015).

2.3.2.9 Criticisms and limitations, of the sleep loss and cognitive performance literature

One reason for the discrepancy in results between studies of sleep deprivation, sleep restriction and complete sleep loss, is that they have employed variants of the Stroop or Go/Nogo task paradigms, tapping into a number of simple and complex cognitive processes. For example, Rossa and colleagues (2014) employed an emotional Go/Nogo task during sleep restriction, which measures not only the ability of participants to successfully inhibit

responses to negative or 'fearful' face-stimuli, but also the cognitive process of affective regulation or emotional control. Similarly, the sleep restriction study by Swann et al. (2006) used the masked priming task incorporating the Go/Nogo method requiring participants to make a timed lexical decision (Go word vs. Nogo non-word). Although this is not typically a measure of response inhibition, it indexes lexical access or the automatic cognitive processes underlying word recognition.

Another potential reason results may not align between studies is that Stroop or Go/Nogo task response inhibition was only one of a larger set of cognitive processes evaluated for the behavioural outcomes (Honma et al., 2015). For example, when examining the effects of sleep restriction on 'cognition' in women, Stenuit and Kerkhofs (2008) combined numerous behavioural outcomes. Their research combined errors on Go stimuli, which is a cognitive index of automatic motor-attention processes (Stenuit & Kerkhofs, 2008). With errors on Nogo stimuli, this is an index of the executive function of response inhibition, providing an overall composite measure of 'total errors' on the Go/Nogo task. This essentially measures the overall accuracy of the Go/Nogo task but does not provide information on automatic processing or response inhibition separately. Similarly, Stenuit and Kerkhofs (2008) also measured 'total reaction times' on the Stroop task which is inclusive of incorrect response times to word-colours for both matching and non-matching word-pairs (MacLeod, 1991). Hence changes in performance between studies could also be due to variations in either executive functioning or the basic underlying cognitive processes of vigilance and attention (Honma et al., 2015; Swann et al., 2006).

Since performance on many cognitive tasks requires both basic cognitive processes and higher order executive functions, it is necessary to understand which cognitive processes are being assessed. In many studies however, it is not clear which dependent variable or outcome measure is being evaluated. For example, in a series of studies on partial sleep deprivation on the Stroop task, the dependent variable is noted to reflect selective attention and is simply labelled as SA in the methods and referred to as SA thereafter in the discussion of this research (Jarraya et al., 2013; Jarraya et al., 2014).

Adding to the disparity of results between studies is the use of various versions of the Go/Nogo task; including the masked-word priming task (Swann et al., 2006), emotional Go/Nogo task (Rossa et al., 2014), Sustained Attention to Response Task (SART; Manly,

Lewis, Robertson, Watson, & Datta, 2002), Eriksen flanker task (Stroth et al., 2009) and the Stop-signal task (Honma et al., 2015). Similarly, several versions of the Stroop task exist including the classical card version and also the single-trial computerised version of the test with differences in results between computer and card versions (MacLeod, 1991). Not only do variants of the Stroop and Go/Nogo tasks make it difficult to compare results between studies but tasks can also be presented in different formats including visual (Drummond et al., 2006), auditory (Falkenstein, Hoormann, & Hohnsbein, 2002), or even somatosensory (Akatsuka, Yamashiro, Nakazawa, Mitsuzono, & Maruyama, 2015). All sensory input modalities show slightly different processing (i.e., response) times (MacLeod, 1991). Furthermore it is difficult to compare behavioural outcomes of these tasks as they are not standardised for dependent variables such as mean or reciprocal reaction times in milliseconds (ms) as for the PVT. Instead studies have used a wide range of behavioural outcomes or dependent variables for the Go/Nogo task including but not limited too; Hit rate or correct responses on Go trials; RT on correct response for Go trials; Incorrect responses on Go trials (i.e., errors of omission – failing to respond); Correct responses to Nogo trials; False alarms or incorrect responses/errors on Nogo stimuli (i.e., errors of commission – failure to withhold a response). Similarly, studies have also used a wide range of dependent variables for the Stroop task, for example median instead of mean response times or percentage incorrect as opposed to percentage correct on either matching or non-matching word-pairs. Further as dependent variables are rarely presented in the same metric making it difficult to measure between studies for instance comparing rates or proportions (Drummond et al., 2006) to percentages (Sagaspe et al., 2012).

2.3.3 Physical activity/exercise and cognitive performance

Research examining the effect of physical activity or exercise on Go/Nogo task performance presents relatively consistent findings (Akatsuka et al., 2015; Kamijo et al., 2004; Stroth et al., 2009). Mean response times on Go trials have not been shown to be affected following 15 minutes of treadmill running at 50% VO_{2max} (Akatsuka et al., 2015), or following a low-, medium-, or high-intensity pedalling exercise (Kamijo et al., 2004). However time-of-day effects have been shown with physical activity (Petit, Bourdin, Mougin, Tio, & Haffen, 2013). Professional male competitive cyclists performing a maximal-intensity exercise followed by morning and evening cognitive test sessions showed significantly lower response times to Go stimuli in the afternoon test compared to the morning (Petit et al., 2013). Although, as

mentioned, response times on Go trials only indexes automatic motor vigilance, whereas the effects on response inhibition as measured by errors on Nogo trials has received less attention in adults. Although in adolescent samples a single bout of aerobic exercise has not been shown to effect response times to Go stimuli, percentage of missed Go stimuli or false alarms on Nogo trials (Stroth et al., 2009).

The effects of exercise on the Stroop task have also been reported (Yanagisawa et al., 2010). Healthy young male and female participants were tested 15 minutes after cycling at 50% VO_{2max}. Results showed a significant interaction between the exercise and control conditions on pre and post response times to Stroop interference. Results showed that Stroop interference response times improved in the exercise condition as compared to the no exercise condition. Further, other research has also demonstrated that a single session of rigorous exercise improves Stroop interference performance (Hogervorst, Riedel, Jeukendrup, & Jolles, 1996).

While comparisons between athletes and firefighters are problematic, as outlined in Section 2.2.15, a recent study has shown that BMI is not significantly correlated with Stroop task interference performance (Yesavage et al., 2014). However, the results did report that BMI related disorders such as hypertension or diabetes were associated with poorer task performance. This suggests that declines on the Stroop task are associated with obesity-related disorders, although a direct link between obesity and poor performance is not substantiated.

2.3.4 Effects on Stroop and Go/Nogo tasks of physical activity and heat

From major reviews examining the impact of heat on cognitive performance it is clear that the type of task, duration of exposure to heat and intensity of temperature all influence cognitive performance (Hancock, Ross, & Szalma, 2007; Hancock & Vasmatzidis, 2003). More importantly, for the context of wildland firefighting, there is some evidence that heat with physical activity can result in cognitive performance deficits.

Cognitive performance changes whilst performing physical activity in hot temperatures has been the focus of several studies independent of dehydration (Azer, Monall, & Leung, 1972; Griffiths & Boyce, 1971; Iampietro et al., 1972; Sharma et al., 1983). Comprehensive

research on heat stress subjected workers to a heat-acclimatisation schedule in a heat chamber for eight consecutive days at 49.0°C (T_{db}) (Sharma et al., 1983). Following this heat-acclimatisation period participants underwent exposure to 4 h in a climactic chamber at temperatures from 29.4°C to 51.5°C (T_{db}). Inside the chamber participants completed a step up and down exercise on a 39 centimetre stool at a rate of 15 steps per minute for 30 minutes followed by 30 minutes of rest. This work-rest cycle was repeated four times with water provided *ad libitum* during rest breaks. Simple cognitive measures of associative learning, reasoning ability, mental alertness, and dual-task performance were all impaired in terms of both accuracy and speed under high thermal stress. The reported deterioration of cognitive performance with heat exposure and physical activity is consistent with previous findings (Iampietro et al., 1972). The results by Sharma et al. (1983) also reflect studies on dual-task performance reporting a deterioration in efficiency with higher temperatures and physical activity (Azer et al., 1972; Griffiths & Boyce, 1971). The only discrepancy is a temperature of 32.2°C (T_{db}) is identified by Sharma and colleagues (1983) as the critical temperature beyond which mental functions begin to deteriorate, as opposed to previous reports of 29.4°C (T_{db}; Azer, Monall, & Leung, 1972; Griffiths & Boyce, 1971; Iampietro et al., 1972). In any case, heat as a thermal stressor in any situation results from a complex interaction of several factors; air temperature, radiant heat, and an individual's metabolic heat load (Larsen, Snow, & Aisbett, 2015). Importantly, Sharma and colleagues directly highlighted the critical temperature beyond which simple cognitive performance deteriorates is 32.2°C (T_{db}) for moist conditions. This is slightly higher for hot-dry conditions at 33.3°C (T_{db}). The authors recommended that in order to maintain cognitive functioning in personnel working continuously for four hours the thermal environment should not exceed 31.1°C (T_{db}) in hot-humid conditions and 32.2°C (T_{db}) in hot desert conditions.

The effects of physical activity and heat on Stroop task performance have also been examined in industry personnel (Mazloumi et al., 2014). Male workers exposed to heat stress in an iron casting unit completed the Stroop task before starting work and then during the shift. The average temperature ranged from 16.75°C to 35.4°C for the control group with a normal air-conditioning and 30°C to 32.6 °C in the heat condition. Results demonstrated that workers in the heat condition showed impaired response times and an increased number of errors compared to the control group on the Stroop task. Additionally, response times and errors in the heat condition increased from testing sessions starting before work as compared to during the shift. The effects of exercise in the heat have also been examined for the Go/Nogo task,

with findings contrasting those reported for the Stroop task. Cycling at a heart rate of 160 beats per minute for 10 minutes at a temperature of 35°C did not significantly affect response times on Go trials as compared to resting conditions or following neck cooling (Ando et al., 2015).

2.3.5 Effects on cognitive performance of sleep restriction and physical activity

Insight on the effects of multiple stressors on cognitive performance such as consecutive nights of sleep loss and physical activity can be gained from studies of military operations. In an early study young healthy adult cadets were scheduled to either 0 h, 3 h, or 6 h total sleep during a four to five day strenuous combat course completing tests of cognitive performance throughout (Opstad, Ekanger, Nummestad, & Raabe, 1978). The weather was noted to be mostly sunny and warm during the day but cool at night. Results showed substantial and progressive impairment for all conditions on tests of visual vigilance, reaction time, digit-symbol substitution, sorting, rifle-shooting and memory. The results also demonstrated that the groups receiving 6 h and 3 h of sleep obtained slightly better results on all cognitive measures than the group with 0 h scheduled sleep.

In a similar sleep restriction military study cognitive performance was measured in 10 young infantrymen during a nine day tactical defence exercise (Haslam, 1982). The participants were scheduled to an initial sleep deprivation period of 90 h, followed by 4 h sleep per 24 h, for six nights. Military aspects of the trial included digging, camouflaging and occupying trenches, surprise ‘enemy attacks’, mine laying and clearing and first aid. A 20% performance reduction was seen in vigilance rifle-shooting compared to control values, reflecting the effect of the total sleep deprivation period and also the subsequent effect of the sleep restriction period. The results suggest that a self-paced task is less likely to deteriorate from sleep loss compared to an experimenter-paced task with a high vigilance requirement. Results also showed logical reasoning declined after one night without sleep and decoding (a mechanical task) declined after two nights without sleep. Performance on both tasks reflected a speed-accuracy trade-off, such that speed deteriorated but accuracy was preserved compared to the control condition. Haslam (1982) concluded that as little as 4 h sleep per 24 h had a clear marked beneficial effect on performance compared to no sleep at all. The only

exception was at 05:45 h, the time coinciding with a circadian nadir in cognitive performance driven by a homeostatic need for sleep and phase of the circadian rhythm (Colquhoun, Blake, & Edwards, 1968). The findings from these earlier military studies (Haslam, 1982; Opstad et al., 1978) also mirror sleep dose-dependent cognitive declines reported in later large-scale chronic sleep restriction studies (Belenky et al., 2003; Dinges et al., 1997; Van Dongen, Maislin, et al., 2003).

Another study by Haslam (1984) assigned three platoons to either 0 h, 1.5 h, or 3 h sleep per 24 h for six consecutive days following an initial four day complete sleep loss period. Military exercises throughout the study were conducted in cold, wet and windy weather conditions (3-18°C). Vigilance and the more complex cognitive tasks deteriorated the most, whilst simple or lower order and well-learned tasks were the least affected. For all cognitive tasks including logical reasoning, short-term memory and map-plotting (encoding/decoding) results showed a general rapid decline in performance over the first four days of sleep loss. Declines in cognitive performance plateaued for the remaining days of sleep restriction. Notably, there were no overall significant differences between the three platoons receiving 0 h, 1.5 h, or 3 h sleep per 24 h for six nights, with all conditions producing comparable cognitive deficits.

2.3.6 Effects on cognitive performance of sleep loss and heat

The combined effect of sleep deprivation and temperature on cognitive performance was first studied by Pepler (1959) in young physically fit British Royal Navy sailors. The four experimental conditions were one night's sleep or one night's sleep loss in either cool or hot ambient temperatures. Participants were tested twice in two consecutive weeks, for each week they worked once with and once without sleep on the previous night, once in the cool and once in hot temperatures. During the cool periods air temperature was 21°C inside the climatic chamber and during the hot period temperature was set to 38°C. There were no significant interaction effects of sleep loss and heat combined on the tracking and serial choice tasks, although heat and sleep loss individually affected performance on both tasks in different ways. Generally, sleep loss was associated with reduced activity in both tasks, whereas heat increased the number of responses although at a reduced accuracy. The authors surmised that the effects of warmth and sleep loss were not governed by similar mechanisms

as previously proposed by Lee (1950), due to the finding that sleep loss and warmth did not have the same effect on cognitive performance.

Poulton, Edwards, and Colquhoun (1974) later conducted a follow-up experiment to Pepler's (1959) study. They posited that the non-significant interaction shown between heat and sleep loss may have been masked by his use of the logarithmic transformations of raw scores to meet the assumption of normality, in order to conduct parametric statistical tests (i.e., ANOVAS) for the results. Poulton et al. (1974) replicated the experiment and applied non-parametric statistical tests (i.e., Wilcoxon's U) to the raw scores to reveal if there were any significant interactions between heat and sleep loss on measures of cognitive performance. Like Pepler (1959), Poulton and colleagues' (1974) sample consisted of 12 young naval men who completed cognitive performance measures following conditions of one night with and one night without sleep, in a cool temperature (21°C) and also in the heat (32-38°C). No significant interaction effects between sleep deprivation and heat were seen for the five-choice task or tracking with peripheral lights task, however there was a significant interaction effect on the first half of the Wilkinson auditory-vigilance task. For the vigilance task, adding heat to sleep loss was an advantage, however at the end of the task the relationship was reversed and adding heat to sleep loss was disadvantageous. Poulton et al. (1974) concluded the results of the auditory tracking task may indicate that heat exposure can serve as an arousal stressor and can potentially improve, or mitigate sleep loss performance decrements, shifting performance closer to baseline.

2.3.7 Effects on cognitive performance of sleep loss, physical activity and extreme ambient temperatures

Insight into the effects of exposure to the three stressors of sleep loss, heat, and physical activity simultaneously on cognitive performance comes from a handful of simulated combat military exercises conducted in the field and laboratory. US Army officers on active duty completed a field exercise for training purposes (Lieberman, Bathalon, Falco, Morgan, et al., 2005). The exercise was conducted in hot-humid temperatures with a maximum ambient temperature of 31°C and daily minimums of 19°C. In the 27 h before the field exercise began participants slept a total of 5.3 h and throughout the field deployment (53 h) they slept a total of 3 h, consisting mainly of naps (average number 14.4) with a mean duration of 12.3

minutes. Results revealed severely degraded performance on cognitive tests of scanning visual vigilance, four-choice visual reaction time, matching-to-sample, repeated acquisition and grammatical reasoning. More importantly, the performance decrements exceeded those observed in earlier laboratory studies on single stressors. For example, the results showed the number correct on a grammatical reasoning task declined 15% after 53 h of TSD deprivation as compared to previous reports of 7% under a 60 h TSD protocol (Newhouse et al., 1989). The results showed that even well-trained leaders experience a significant deterioration on range of tasks of cognitive performance from simple measures of vigilance such as response time through to higher order cognitive functions such as learning, memory and reasoning. Furthermore, the magnitude of decrements observed in cognitive performance throughout the training exercise were also consistent with anecdotal observations made by soldiers, police, firefighters, disaster victims and other personnel in high-stress environments (Lieberman et al., 2007). These results also mirror previous findings from other military field studies with substantial improvements in cognitive performance revealed when sleep is eventually obtained (Haslam, 1984; Lieberman, Tharion, Shukitt-Hale, Speckman, & Tulley, 2002; Opstad et al., 1978).

Lieberman et al. (2006) noted that field-studies inherently involve substantial, uncontrollable variations in the nature and extent of stressors present and extensive systematic cognitive testing is difficult in such settings. In an attempt to reconstruct combat-like stressors, Lieberman et al. (2006) developed a carefully controlled laboratory simulation of sustained military operations. The protocol was designed to simulate a brief 84 h of SUSOPS or the equivalent civilian activity such as disaster relief. Young healthy male soldiers completed a three and a half day exercise obtaining a total of 6.2 h sleep during the 84 h of SUSOPS in temperatures ranging from 7°C to 30°C. Performance declined on three of the four cognitive tests (visual vigilance, four-choice RT, and matching-to-sample tasks) after 49 h, further declining by 73 h into the SUSOPS, compared to baseline measures. The Repeated Acquisition test, a more complex task of motor learning and memory did not however show any impairment. These findings may suggest that simple tests of cognitive performance are more sensitive to the effects of multi-stressor environments than complex tasks. This is consistent with the findings from other SUSOPS studies, where caffeine was available as an intervention (Lieberman et al., 2002; Lieberman, Wurtman, Emde, Roberts, & Coviella, 1987). Importantly, this research was able to draw direct comparisons with field studies conducted with US Army Ranger Officers (Lieberman, Bathalon, Falco, Morgan, et al., 2005)

and US Navy SEAL trainees (Lieberman et al., 2002) during 'Hell Week'. Performance observed in the ranger study was nearly identical to performance during SUSOPS, with declines of 72% and 67%, respectively, from the overall mean of cognitive performance measures, in contrast to a decline of 143% in Navy SEAL trainees (Lieberman, Bathalon, Falco, Morgan, et al., 2005; Lieberman et al., 2002).

The study by Lieberman et al. (2006) highlighted two important findings. First, laboratory-based studies can accurately and reliably simulate environmental stressors and produce cognitive performance deficits similar to those observed in the field. More importantly, the research highlighted that the environmental and occupational stressors present during a field exercise vary in intensity, as does their impact on cognitive performance. For example, the cognitive declines shown for a US Army Ranger during a military exercise (Lieberman, Bathalon, Falco, Morgan, et al., 2005) were relatively mild compared to the deficits observed in trainees during Navy SEAL 'Hell Week' (Lieberman et al., 2002).

2.3.8 Summary, limitations of present research and recommendations for future research

In summary, studies are available on the cognitive performance of structural firefighters in hot external temperatures (Smith, Manning, et al., 2001; Smith & Petruzzello, 1998), although the effect of heat in combination with sleep restriction remains to be quantified for wildland firefighters. Shortened sleep, hot temperatures and physical activity individually and in combination have been shown to result in diminished performance on a range of cognitive tasks (Belenky et al., 2003; Cain et al., 2011; Dinges et al., 1997; Drummond et al., 2006; Stenuit & Kerkhofs, 2008; Van Dongen, Maislin, et al., 2003). However, less available is research on the effects of these three stressors in combination.

Studies in military settings provide some useful insight into the effects of exposure to a combination of stressors of heat, physical activity, and inadequate sleep (Haslam, 1982, 1984; Lieberman, Bathalon, Falco, Kramer, et al., 2005; Lieberman, Bathalon, Falco, Morgan, et al., 2005; Lieberman et al., 2006; Lieberman et al., 2002; Opstad et al., 1978). However, these studies involve substantial, uncontrollable variation making it difficult to know which factors

are impacting performance. In addition, extensive systematic cognitive testing is difficult to conduct in the field and is often impractical during fire suppression operations.

Nonetheless, research has shown that a controlled laboratory simulation equivalent to a three and half day disaster relief (Lieberman et al., 2006) replicated cognitive deficits comparable to those observed in field (Lieberman, Bathalon, Falco, Kramer, et al., 2005).Whilst these military studies also provide valuable insight into the effect on cognitive performance of sustained physical activity in extreme environments, the initial periods of complete sleep deprivation are not characteristic of wildland firefighting. Rather, volunteer firefighters are exposed to sleep restriction that usually accumulates across consecutive shifts (Cater et al., 2007; Vincent et al., 2016). Furthermore, volunteer firefighters are exposed to low-intense physical labour interspersed with bouts of moderately high-intense activity (Barr et al., 2010). While laboratory-based designs consist of exercises that are not reflective of firefighter work rates or activities such as cycling.

One other limitation of the present research literature is that the majority of studies have used exclusive samples of homogenous young fit healthy males, with few exceptions (Belenky et al., 2003; Dinges et al., 1997; Van Dongen, Maislin, et al., 2003). Similarly, one of the most widely cited studies of sleep restriction employing both Go/Nogo and Stroop tasks included females only (Stenuit & Kerkhofs, 2008). Given that firefighter agencies worldwide consist of both males and females, and a range of ages, it is important to document the consequences of sleep restriction in both. Further, future research may also want to focus on cognitive performance during a laboratory simulated design of wildland firefighting with temperature manipulations, sleep restriction and firefighter relevant physical tasks. Or alternatively, examine cognitive performance during real life wildland fireground tour campaigns in the field.

Chapter 3: General Methodology

3.1 Ethics

For Studies 1, 2, 3, and 4, standard, hot, sleep restriction, and sleep restriction with heat protocols were developed in consultation with guidelines by the National Health and Medical Research Council of Australia. For all studies presented in this thesis ethics approval was obtained from the CQUniversity (H12/01-016; Appendix A) and Deakin University Human Research Ethics Committees (2010-170). To participants it was made clear the right to withdraw their participation at any stage, without due reason. Participants did not receive any remuneration for their participation in any of the studies contained in thesis. For all research data participants were assigned an alphanumeric code to ensure their confidentiality and anonymity.

3.2 Participants

3.2.1 Recruitment

Potential participants were recruited via posters, advertisements and fliers (see Appendices B and C), posted on local and interstate fire department notice displays and provided at board meetings, with additional recruitment sessions held at the worksite. Recruitment fliers were also shared on various social networking websites such as Facebook and Twitter. Participants were volunteer firefighters recruited from the Country Fire Service (South Australia), Country Fire Authority (Victoria), Tasmania Fire Service, New South Wales National Parks and Wildlife Service, and Australian Capital Territory Fire and Rescue. Interested participants contacted either the Appleton Institute or Deakin University sports science and nutrition division, via telephone or e-mail. Participants were then provided with information about the study and what participation would involve. Eligible participants were then provided with an initial mail out by researchers containing an information sheet (Appendix D), consent form (Appendix E), and a medical screening and General Health Questionnaire (GHQ; See appendix F). Participants were also screened and excluded if they had a condition or injury preventing them from carrying out normal fireground duties, a diagnosed sleep disorder such as obstructive sleep apnoea syndrome, or periodic limb movements in sleep, or

a contagious illness (Appendix G). Once the consent form was returned by participants, further contact was made by telephone to confirm a participation date.

3.2.2 Participant demographics

3.2.2.1 Study 1 – Chapter 4

For Study 1 examining temperature and sleep, the *control* condition consisted of 30 participants (27 males [m], 3 females [f]; mean age = 38.7 y, SD = 15.7 y) with a mean BMI of 27.5 kg/m² (SD = 4.8 kg/m²). The *hot* condition consisted of 19 participants (15 m, 4 f; mean age = 34.9 y, SD = 12.7 y) with a mean BMI of 27.2 kg/m² (SD = 3.6 kg/m²).

3.2.2.2 Study 2 – Chapter 5

For Study 2 investigating temperature, sleep restriction, and sleep the *control* condition consisted of 25 male and female participants (22 m, 3 f; mean = 36.7 y, SD = 15.9 y), with a mean BMI of 27.0 kg/m² (SD = 4.8 kg/m²). The *awake* (i.e., sleep restriction) condition consisted of 25 participants (20 m, 5 f; mean = 38.5 y, SD = 13.2 y) with a mean BMI of 29.2 kg/m² (SD = 4.9 kg/m²). The *awake/hot* (i.e., sleep restriction and heat) condition consisted of 11 participants (10 m, 1 f; mean = 37.5 y, SD = 15.6 y) with a mean BMI of 26.7 kg/m² (SD = 4.6 kg/m²).

3.2.2.3 Study 3 – Chapter 6

For Study 3 examining temperature, dehydration, and cognitive performance, the *control* condition consisted of 45 participants (38 m, 7 f; mean age = 36.4 y, SD = 14.2 y) with a mean BMI of 28.3 kg/m² (SD = 4.8 kg/m²). The *hot* condition consisted of 28 participants (24 m, 4 f; mean age = 34.7 y, SD = 13.2 y) with a mean BMI of 26.9 kg/m² (SD = 4.0 kg/m²).

3.2.2.4 Study 4 – Chapter 7

Study 4 investigated temperature, sleep restriction and cognitive performance, different from study 2 examining these effects on sleep architecture. The *control* condition consisted of 23 participants (21 m, 2 f; mean = 36.7 y, SD = 15.9 y), with a mean BMI of 27.0 kg/m² (SD = 4.8 kg/m²). The *awake* and *awake/hot* conditions in Study 4 were the same as in Study 2.

3.3 Procedures and protocols

The wildland fireground tour simulation was comprised of four-nights and three-days with day- and night-time temperature manipulations, physical activity, and/or sleep restriction. All studies in this thesis used the same protocol, with Study 3 examining the baseline day only, so that data for the awake/hot condition could be combined with the hot condition, and the awake condition could be combined with the control condition data on baseline day. On the pre-study night participants arrived via taxi from the airport, or in their own vehicle at either the Melbourne or Adelaide designated location. Local time of the designated study site was used in all studies. The timezone difference between the two study sites was only 30 minutes. Where participants travelled from interstate, the maximum difference in timezone from domicile to study site was also 30 minutes. At 19:00 h or earlier, participants were provided with a main dinner meal and given a presentation outlining all the details of the study, along with video footage of each of the cognitive tasks, physical tests, and sleeping equipment. Following dinner, at approximately 19:30 h participants were shown the physical tasks and completed task familiarisation, participating in repeated practice trials, around one to three or until the learning curve was assumed complete. After physical task familiarisation was complete, at approximately 20:30 h, participants were introduced to the cognitive test battery including the PVT, Go No/go and Stroop tasks, completing one to three practice trials, to reduce any potential practice effects (Sagaspe et al., 2006).

From 21:00 h to 22:00 h participants were wired-up for sleep and then provided with an 8 h baseline sleep opportunity (time in bed [TIB] 22:30-06:30 h). This was followed by three nights of 8 h sleep opportunities (TIB 10:00-06:00 h) for the *control* and *hot* conditions (see Figure 3.1), or two experimental nights of 4 h sleep opportunities (TIB 02:00-06:00 h), followed by an 8 h recovery sleep (TIB 10:00-06:00 h), for the *awake* and *awake/hot* conditions (see Figure 3.2). For the *control* and *awake* conditions, day- and night-time temperatures remained consistent between 18-20°C, throughout the three-day, four-night protocol. The baseline night was also consistent for all conditions with night-time (18:00–06:30 h) temperatures set between 18-20°C. On baseline day from 06:00-11:15 h temperatures were set between 18-20°C for all conditions. Then on baseline day at approximately 11:15 h temperature in the *hot* and *awake/hot* conditions was raised from 18-20°C to 33-35°C for the remaining duration of the simulated work shift (11:30-18:00 h). This temperature remained consistent for the *hot* and *awake/hot* conditions over experimental days

one and two for the simulated work shifts (06:00-18:00 h), whilst night-time (06:00-18:00 h) temperatures were subsequently lowered to 23-25°C for the experimental nights and recovery. Temperature ranges of 18-20°C, reflect cool to mild day- and night-time temperatures experienced in the field, such as during the 'Black Saturday' fires, while temperature ranges of 33-35°C, during the day, and 23-25°C at night, reflect warmer field conditions (Aisbett et al., 2012; Raines et al., 2015; Raines et al., 2012, 2013).

Due to the nature of volunteer firefighting work individuals are responding in the case of emergency relief, and therefore unlike career or salaried firefighters, are not required to be at work during specified times, and hence are not provided with work rosters by each individual State fire agency (Aisbett et al., 2012; Vincent et al., 2016; Vincent et al., 2018). Although, during multi-day fire deployments wildland firefighters are required to work either 12 h day- or night-shifts (see Figure 3.1), and these can be extended, depending on the severity of the fire, for up to 15 h to 16 h, with each deployment lasting approximately three to five consecutive days (Aisbett et al., 2012; Cater et al., 2007; Phillips et al., 2007). During these day- and night-shifts volunteer firefighters work conditions reflect prolonged periods of low-intense physical labour interspersed with bouts of moderately high-intense physical activity (Barr et al., 2010). The simulated work-shift consisted of regular intermittent physical work circuits designed to simulate wildland firefighting (Barr et al., 2010). Briefly, each of the physical work circuits were comprised of six exercises including raking, charged hose advances, black out hosing, making up on the bite, lateral repositioning, and static hose holding. Each circuit was co-ordinated by a central timer with a pre-determined work-to-rest ratio and was self-paced by individuals determining the number of repetitions they could complete. These physical tasks have previously been recognised by firefighters as being characteristic of the typical carry and drag activities that comprise the key firefighting tasks frequently performed on the fireground (Lord et al., 2012; Phillips et al., 2012). Also, each of the tasks have been validated in replicated laboratory settings by physiological measurements as compared to those taken on the field during wildfire suppression for frequency, task duration and intensity (Lord et al., 2012).

On baseline and experimental days physical work circuits were conducted at the same overlapping times each day from 08:00-08:55 h; 10:00-10:55 h; 12:30-13:25 h; 14:30-15:25 h; and 16:30-17:25 h (for a more detailed methodology on the physical work circuits the reader is referred to Vincent et al., 2015). Following each physical work circuit physiological testing

was conducted from 08:55-09:20 h; 10:55-11:20 h; 13:25-13:50 h; 15:25-15:50 h; and 17:25-17:50 h (for a more detailed methodology on physiological testing for e.g., grip strength, blood pressure, and lung capacity etc., the reader is referred to Larsen, Snow, & Aisbett, 2015). Finally, subsequent to each physiological testing session cognitive testing was performed at the same overlapping times each day with trials at 09:20-09:45 h; 11:20-11:45 h; 13:50-14:15 h; 15:50-16:15 h; and 17:50-18:15 h.

In the morning following the recovery night's sleep participants were given an opportunity to provide feedback on the reliability and validity of tasks and conditions employed in the protocol, in a semi-structured post-experiment debrief. Participants were also given the opportunity to raise any queries, questions or concerns that they may have had and then completed a post-testing illness and injury questionnaire (Appendix G). After debriefing, the participants were then transported via taxi using University cabcharges to the Adelaide Airport, South Australia, or Melbourne Airport, Victoria, depending on the testing site.

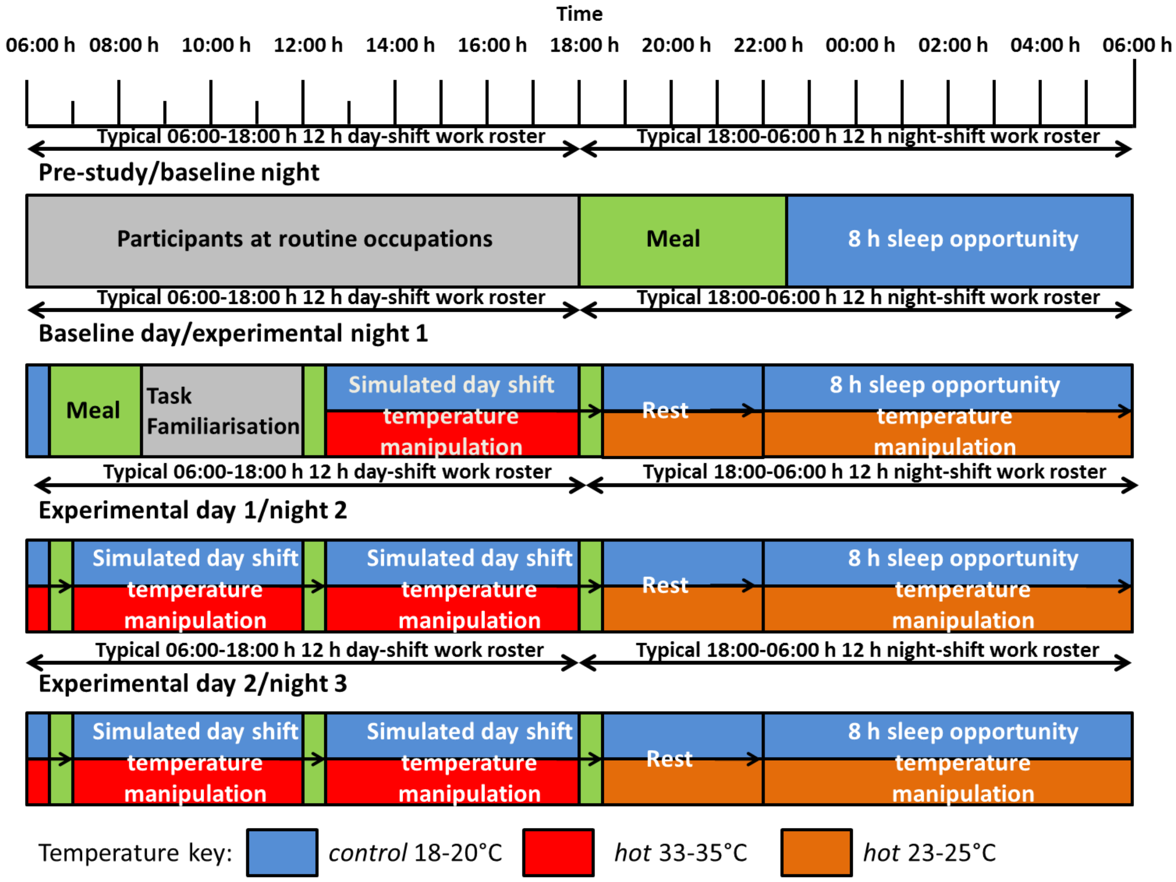

Figure 3.1 Experimental protocol for *control* and *hot* conditions. Studies 1, 2, 3, and 4.

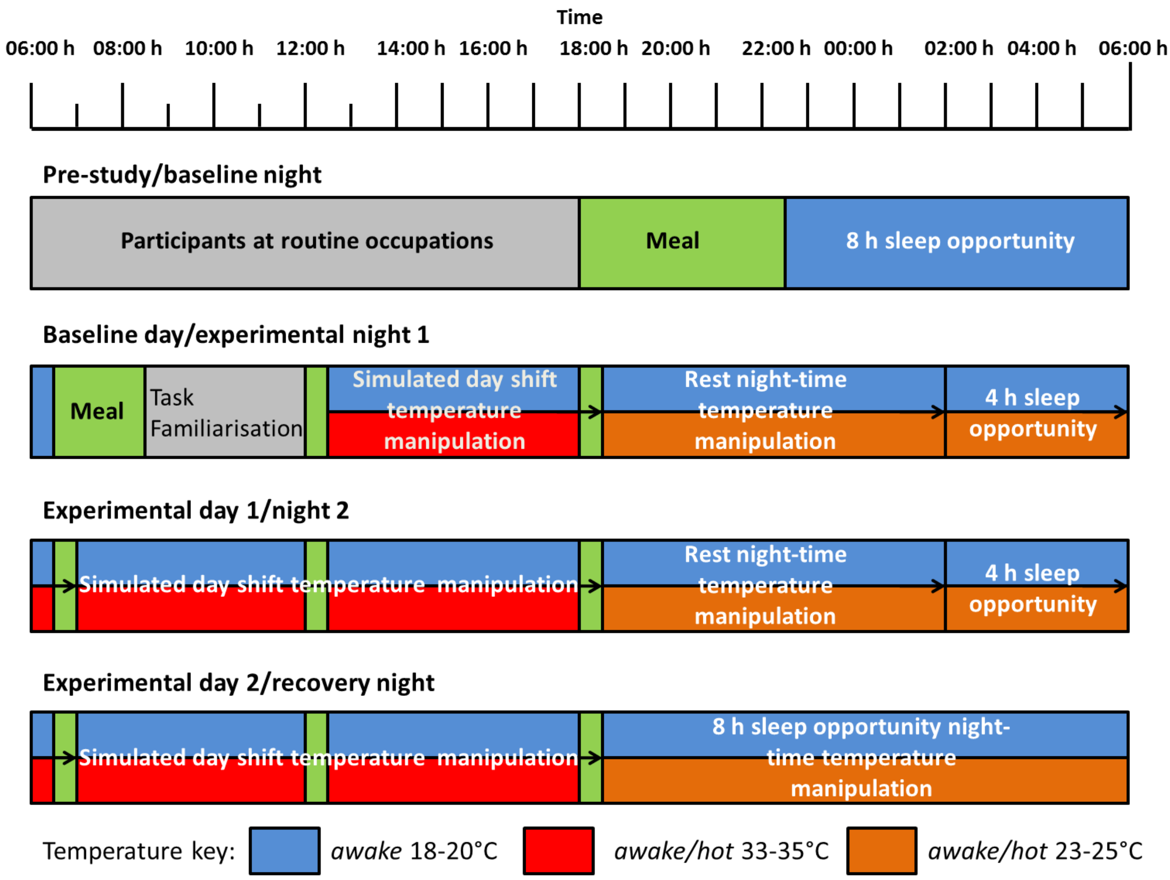

Figure 3.2 Experimental protocol for the *awake* and *awake/hot* conditions during the day- and night-times. Studies 2 and 4.

3.4 Laboratory conditions

In Melbourne, the simulated laboratory was set-up at Victoria, City of Whitehorse in the Matsudo Room located in Box Hill Town Hall. In Adelaide, the simulated laboratory was set-up at the Country Fire Service state training facility, located in Brukunga, South Australia. During the course of each study, participants in the laboratory environment were isolated indoors from natural sunlight, although time cues were present and frequent rest breaks outside were provided. During rest breaks participants were provided with coffee and allowed to smoke should they chose. Rest breaks were provided for all participants in each study hence any potential confounding effects from these rest breaks would be generally equivalent across conditions and studies. Each study was configured in such a way that up to five participants could be studied at a time, with each participant sleeping under the same conditions in one room. For each sleep opportunity to simulate wildfire suppression conditions, participants were provided with Kookaburra™ sleep stretchers, matching inflatable mattresses, and sleeping bags with accompanying pillows, cases and hygienic sleeping bag in-liners. Temperature for each study was maintained at both facilities using reverse cycle air-conditioning, central thermostat heating and additional portable heaters. Body temperature was also measured and reported in more detail elsewhere please see Larsen et al (2015). To ensure consistency temperature was continuously monitored, maintained and recorded by a wireless temperature and humidity logger (HOBO ZW_003, One Temp Pty Ltd, Australia), three data receivers (HOBO ZW_RCVR, One Temp Pty Ltd, Australia) and included software (HOBO Pro Software, One Temp Pty Ltd, Australia).

3.4.1 Food and fluid

Firefighters were instructed, as per agency prescribed guidelines, to consume water, add electrolyte satchels and eat food from standardised personalised ration packs as desired or *ad libitum*. All food and fluid intake was recorded by researchers. Water was stored in the simulation room with no cold beverage provisions outside of main meal times to simulate beverage storage in lockers on-board firefighter vehicles situated in wildfire temperatures (Vincent et al., 2016). Dietary intake was standardised across main meals, with options available at breakfast, consisting of one or two pieces of white or multi-grain toast, one or two fried eggs, rashers of bacon (average two), tea, coffee, and either orange or apple fruit

juice. Lunch was catered by a Subway™ platter, with Emily's Kitchen™ microwave meals for dinner. Personalised ration packs consisted of a set amount of items including The Natural Confectionary Company™ soft lollies, Uncle Tobys™ sultanas and muesli bars, and Arnott's™ dry biscuits.

3.5 Materials and equipment

3.5.1 Psychomotor Vigilance Task

The PVT is a preferable measure as it is relatively straightforward to use, showing diminutive practice effects with a learning curve of one to three trials and provides one of the only tested and validated prerequisites sufficient to assay both performance and the effects of sleep loss (Dorrian, Dinges, & Rogers, 2005). The PVT measures how fast participants respond to a luminous-white-light digit target stimulus, by pressing a response button as quickly as possible with the opposable digit of their dominant hand. The display presents the visual stimulus, counting from zero to 60 seconds in one millisecond intervals. When the participant reacts by pressing the response button, the light-emitting diode (LED) display pauses and the reaction time is displayed for one second precipitating feedback to the participant. Following a response the counter is subsequently reset and this process is repeated, similarly, if there is a null response over 60 seconds the timer also resets. Participants were instructed to press the response button as quickly as possible every time the stimulus appeared in order to optimise reaction time. In addition, participants were instructed to avoid responding prematurely before the counter stimulus commences, as this results in a false start error 'FS', being displayed on the screen. Similarly, if the non-dominant response button is pressed, a 'Please do not push this button', error message is displayed. The PVT inter-stimulus interval, that is, the time between successive presentations of the stimulus, varies randomly between 2,000 and 10,000 milliseconds. This produces near 45 responses, per five minute trial.

The PVT was tailored by the Walter Reed Army Institute for use on the personal digital assistant (PDA) (Lamond, Dawson, & Roach, 2005; Thorne et al., 2005). The PVT software was presented on the Tungsten E PalmPilot (Palm Inc., Sunnyvale, California). The PDA is a plastic portable handheld device (weight, 127 grams; dimensions, 114 mm by 57 mm by 10 mm). The visual RT stimulus is presented on a black and white LED liquid crystal display

screen (3.2 cm by 3.2 cm), with the ostensible surface also containing two response buttons (1.1 by 1.1 cm; see Figure 3.3).

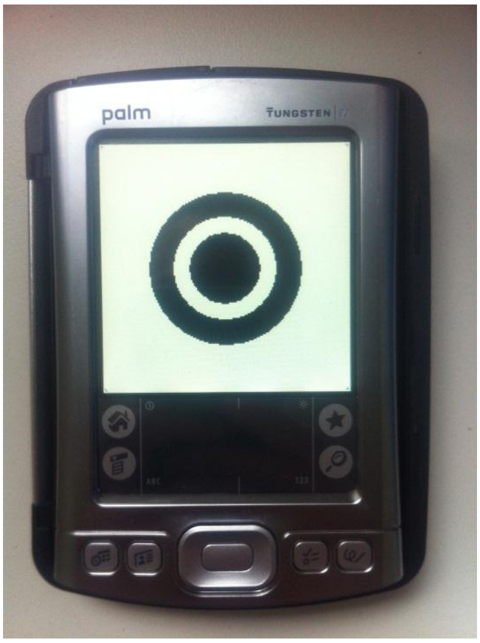

Figure 3.3 Psychomotor Vigilance Task. Presented on a Tungsten E71© PDA with PalmPVT software 300™.

3.5.2 Stroop task

The Stroop task relies on higher-order cognitive processes and is a measure of the executive function of inhibitory control, requiring planning, and selectively co-ordinating a correct response by focusing on the relevant stimuli and suppressing distracting material (Sagaspe et al., 2006). The Stroop task requires participants to input the font colour of a word, as opposed to what it reads, in two different trials. In the first trial participants respond to a matching colour-word, where the word is presented in the same font colour as what it reads (see Figure 3.4). In the matching colour-word trial participants are essentially reading the word without considering the colour of the font, hence the test is relatively simple and straightforward. In the second trial participants are presented with a non-matching colour-word, where the word is presented in a different font colour from what it reads (see figure 3.4). In the non-matching colour-word trial participants are required to suppress the dominant urge to input the read word, and input the actual colour of the word itself. This produces a phenomenon known as the 'Stroop effect', where if the word is different from the colour then the participant

consistently shows hesitation and a longer time to respond in contrast to the matching colour-word trial (MacLeod, 1991). The instructions given by researchers to participants were to press the corresponding colour coded keypad as quickly and as accurately as possible, using their dominant hand, in response to the colour of the word presented. Each testing trial had a duration of two minutes. The participants were given a number of practice tests to alleviate potential learning and practice effects (Sagaspe et al., 2006). The Stroop task is presented to the participant via a standard laptop pc screen (17" screen, resolution, 1280p by 800p; see Figure 3.4).

Figure 3.4 Stroop task. Matching and non-matching, colour-word pair trials.

3.5.3 Go/Nogo task

The Go/Nogo task measures the executive function of response inhibition which is an internally generated component of higher-order control, referring to the ability to deliberately suppress a dominant, automatic, or pre-potent response, when that response is no longer required, or necessary (Drummond et al., 2006). The Go/Nogo task is a validated neuro-cognitive assay shown to be sensitive to the effects of sleep loss (Drummond et al., 2006). In the Go/Nogo task the participants were presented with one of four shape images shown in the centre of the screen, for a period of 200 milliseconds, followed by a black screen interval of 1300 milliseconds (see Figure 3.5). Three of the shapes shown were "Go" images requiring a response, whilst one was a "Nogo" image, requiring no response. Each test had an average of four minutes and 35 seconds, displaying 181 images with a mean of 63% consisting of "Go" images (median range of 61.88% - 68.3%). Two geometric shapes of large and small sizes in homogenous colour were shown for each test. Participants were instructed to press the space bar as quickly and as accurately possible, with their dominant index finger in response to "Go" images, and refrain for 1.5 seconds on the "Nogo" images, until the next stimulus was presented. Six different versions of the test were constructed as is standard in

previous research (see Figure 3.5; Drummond et al., 2006). Prior to commencement of baseline testing, participants were required to perform at a competent level on a practice version of the test in order to eliminate any potential learning effects and reduce errors in response to “Nogo” stimuli (Drummond et al., 2006). The Go/Nogo task was presented to the participant via a standard laptop pc screen (17” screen, resolution, 1280p by 800p).

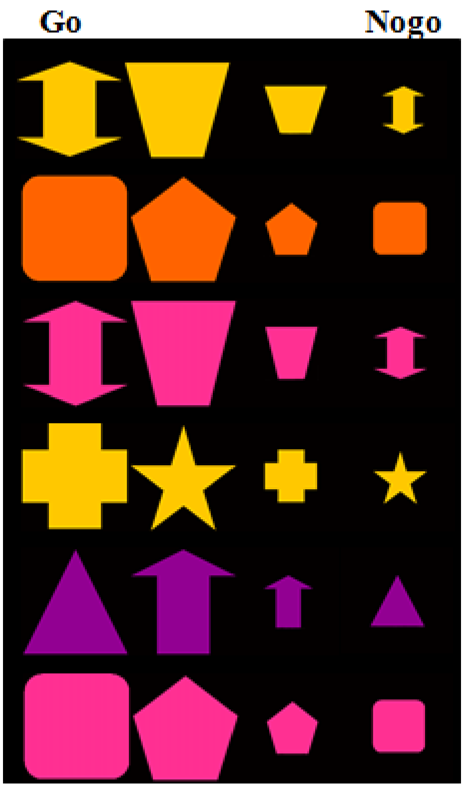

Figure 3.5 Go/Nogo task. The column down shows each of the six versions of the task and each row displays the three “Go” images and one “Nogo” image.

3.5.4 Firefighter personal protective clothing

Personal protective clothing is intended to safeguard the firefighter against environmental hazards and injury (Son et al., 2014). Throughout the duration of the study firefighters were instructed to adhere to normal work practices wearing firefighter PPC, as is the fire-industry standard for every fire agency. PPC consists of a fire retardant jacket, pants, gloves, boots, goggles, and hard-hat. Inter-agency variation exists with PPC but generally the total weight ranges between 8.2 kg and 9.4kg (Son et al., 2014).

3.5.5 Activity Monitor

Participants were required to wear an Actical Z-series activity monitor (Philips Respironics, Inc.), during each study, choosing either the dominant or non-dominant wrist, with participants' choice of wrist documented. The activity monitor weighs 16 grams, containing an omni-directional piezoelectric accelerometer sampling movement at a rate of 32 Hz. Data is collected in activity counts of one minute epochs and stored on-board the 32 MB actical non-volatile memory.

3.5.6 Polysomnography

Sleep was recorded using the Siesta Portable EEG system (Compumedics, Melbourne, Victoria, Australia). A standard montage of electrodes was applied; two channels of electroencephalography (C4-M1, C3-M2); left and right electro-oculograms; left outer and right canthi [LOC-ROC]); and two channels of chin electromyography. One and a half hours prior to bedtime, each participant had PSG Grass^{TM} gold-cup electrodes (Astro-Med, Inc., West Warwick, RI) applied to their face and scalp. Signals for each portable siesta transmitted wirelessly to designated participant laptops located in a separate room monitored overnight by a sleep technician. Participants were provided with an electronic pager, should they have needed assistance throughout the night and were awoken in the morning by a sleep technician with help to remove the PSG monitoring equipment. Ten minutes prior to scheduled bedtimes all sleep and monitoring equipment was placed into position and participants made themselves comfortable prior to lights out. All sleep records were blinded and analysed by a sleep technician in 30 s epochs in accordance with standard criteria (Berry et al., 2012; Iber, Ancoli-Israel, Chesson, & Quan, 2007).

Chapter 4: The Impact of Temperature on the Sleep Characteristics of Volunteer Firefighters During a Wildland Fireground Tour Simulation

Peer-reviewed publication associated with this chapter (Appendix H)

Cvirn, M. A., Smith, B. P., Jay, S. M., Vincent, G., & Ferguson, S. A. (2015). The impact of temperature on the sleep characteristics of volunteer firefighters during a wildland fireground tour simulation. In: Kennedy, G., & Sargent, C. (Eds). *The Time of Your Life. Australasian Chronobiology Society, Melbourne, Australia*, pp. 18-24.

Nature of Candidate's Contribution, including percentage of total: 85%
Writing and results of the publication.

Nature of all Co-Authors' Contributions, including percentage of total: 15%
Ferguson, S. A. (Writing/editing 7%), Jay, S. M. (Writing/editing 2.5%), Smith, B. P. (Writing/editing 4%), & Vincent, G. (Results 1.5%).

Has this paper been submitted for an award by another research degree candidate (Co-Author), either at CQUniversity or elsewhere? No.

Candidate's declaration

I declare that the publication above meets the requirements to be included in the thesis as outlined in the Research Higher Degree Theses Policy and Procedure

Cvirn, MA	April 2018
(Original signature of Candidate)	Date

Abstract

The purpose of this study was to investigate the effects of temperature on sleep during a simulated three-day wildland fireground deployment. Forty-nine volunteer firefighters (age range=18-62 y; BMI=27.4±4.4, 42 males, 7 females) participated in a three-day, four-night laboratory simulation of a wildland fireground deployment in either a *control* (*n* = 30) or *hot* condition (*n* = 19). The simulation included a baseline night and three experimental nights of 8 h sleep opportunities. Night-time temperatures were set to 18-20°C on all four nights for the *control* condition and 23-25°C on the three experimental nights in the *hot* condition. Daytime temperatures were set to 23-25°C for the *control* condition and 33-35°C for the *hot* condition and participants performed repeated bouts of self-paced physical work activities based on wildfire suppression. Sleep was measured using ambulatory polysomnography and scored in accordance with the latest AASM criteria. Results showed there was no significant main effect of condition, nor were there any interaction effects of condition by experimental night. However there was a significant main effect of experimental night ($p \leq 0.05$) on: minutes of N1, N2, N3 and R sleep, sleep onset latency (SOL) and wake after sleep onset; sleep efficiency; and TST. Post-hoc analyses showed that N1 sleep decreased in the heat but remained constant in the *control* condition. N2 sleep remained constant whilst minutes of N3 and R sleep increased in both conditions across experimental nights. Finally, SOL and WASO initially decreased, whilst TST and sleep efficiency increased in both conditions over experimental nights one and two but were not significantly different from baseline levels on experimental night three. It was concluded that the effect of either thermoneutral or heated environmental temperatures on sleep physiology across a simulated three-day fireground deployment were similar, with the exception of N1 sleep decreasing in the heat, as shown by post-hoc inspection. These results indicate that the sleep architecture of volunteer firefighters was not adversely affected by elevated day and night-time temperatures.

4.1 Introduction

Australia is considered one of the most bushfire prone countries in the world with wildland fires increasing in both frequency and scale over the last decade (Aisbett et al., 2012). This is believed to be associated with a global climactic shift towards hotter, drier summers (Aisbett et al., 2012). Although robust data on rural firefighters' sleep patterns during campaigns remains sparse, reports suggest Australian firefighters experience a sleep curtailment of up to three to six hours per day during multi-day fire campaigns (Aisbett et al., 2012; Cater et al., 2007). The increasing severity and frequency of wildland fires places an increased demand on rural fire agencies and personnel, often requiring extended work shifts of up to 12-15 h, with compromised rest between shifts (Aisbett et al., 2012). Adding to the challenge, firefighters may be required to sleep in conditions of high ambient temperature. The impact of high temperature on sleep has not been measured in firefighters although there has been considerable research devoted to the impact of ambient temperature on sleep in laboratory studies (Bach, Telliez, & Libert, 2002).

Laboratory studies focusing on the effects of high or low ambient temperatures report that within a certain range of ambient temperatures referred to as the zone of 'thermoneutrality', sleep quality and quantity are maximal (Bach et al., 2002; Buguet, 2007). Although a thermoneutral zone is often discussed, a specific ambient temperature is rarely defined and tends to vary across studies (Muzet et al., 1983). However, most agree that in brief exposures of one night or less, as ambient temperature increases, SWS and REM sleep decrease (Haskell et al., 1981; Muzet et al., 1983; Muzet et al., 1984; Schmidt-Kessen & Kendel, 1973). During prolonged exposure to ambient temperatures, there is evidence of a thermoregulatory sleep adaptation mechanism with only slight changes found in sleep architecture at low or high ambient temperatures for long durations (Buguet, Livingstone, Reed, & Limmer, 1976; Libert et al., 1988; Palca et al., 1986). Another paradox is that daytime and night-time temperature manipulations appear to have opposite effects on Stage 3 sleep (Bach et al., 2002; Buguet et al., 1976). Daytime temperature manipulation studies have shown consistent effects on sleep quantity regardless of the method of heating including temperature baths (Horne & Moore, 1985), passive heating (Horne & Staff, 1983), and intense exercise (Horne & Porter, 1975). Demonstrating the ensuing sleep episode will be

marked by an increase in Stage 3 sleep with a simultaneous reduction in REM sleep (Horne & Moore, 1985; Horne & Porter, 1975; Horne & Staff, 1983).

Whilst these studies reveal a number of findings important for the effects of day and night-time temperature manipulations on sleep architecture, they provide limited insight relating to the effects on sleep architecture for the conditions faced by wildland firefighters. This is because research designs, ambient temperatures, and participant samples are largely inconsistent with the environmental and occupational demands placed on firefighters and also their demographic profile. Presently, there are no objective polysomnography measurements of firefighters' sleep either in the field or the laboratory under any ambient temperature ranges (Aisbett et al., 2012; Cater et al., 2007). The purpose of the present study therefore, was to investigate the effect on firefighters' sleep quantity and quality of a simulated three-day four-night wildland fireground deployment conducted under either cool or hot, day- and night-time ambient temperature conditions.

4.2 Methods

4.2.1 Participants

Participants were recruited from the Country Fire Service, Country Fire Authority, Tasmania Fire Service, NSW National Parks and Wildlife Service, and ACT Fire and Rescue. Firefighters participated in a wildland fireground deployment simulation and were assigned to one of two conditions. The *control* condition consisted of 30 participants (27 m, 3 f; mean age = 38.7 y, SD = 15.7 y) with a mean BMI of 27.5 kg/m^2 (SD = 4.8 kg/m^2). The *hot* condition consisted of 19 participants (15 m, 4 f; mean age = 34.9 y, SD = 12.7 y) with a BMI of 27.2 kg/m^2 (SD = 3.6 kg/m^2). Simulations were conducted at one of two sites either; the Matsudo room, City of Whitehorse Melbourne, Vic; or the Country Fire Service state training facility, Brukunga, SA. Prior to testing procedures firefighters provided written informed consent acknowledging the risks and benefits of the study, being reminded participation was entirely voluntary and at any time could withdraw. Ethics approval was obtained from the CQUniversity (H12/01-016) and Deakin University Human Research Ethics Committees (2010-170).

4.2.2 Procedure

The simulated wildland fireground deployment consisted of three 24 h periods involving a baseline night with an 8 h sleep opportunity (TIB 22:30-06:30 h) followed by three experimental nights of 8 h sleep opportunities (TIB 22:00-06:00). For the *control* condition, day- and night-time temperatures remained between 18-20°C throughout the protocol. The baseline night was also consistent for both conditions with temperatures set between 18-20°C. From 11:30 h on experimental day one, temperature in the *hot* condition was set to 33-35°C during the day (06:00-18:00 h), and 23-25°C during the night (18:00-06:00 h) for the remaining experimental days. Temperature was maintained using reverse cycle air-conditioning, central thermostat heating and additional portable heaters. Temperature was recorded by four climate nodes, and monitored continuously to ensure consistency.

4.2.3 Polysomnography and sleeping conditions

Sleep was recorded using the Siesta Portable EEG system (Compumedics, Melbourne, Victoria, Australia). A standard montage of electrodes was applied; two channels of electroencephalography (C4-M1, C3-M2); left and right EOG; left and right outer canthi (LOC-ROC); and two channels of chin electromyography. Prior to bedtime, each participant had PSG Grass^{TM} gold-cup electrodes (Astro-Med, Inc., West Warwick, RI) applied to their face and scalp. Participants slept in a single room (≤ five participants) and were provided with camping sleep stretchers, inflatable mattresses, and sleeping bags with accompanying pillows, cases and hygienic sleeping bag in-liners. All sleep records were blinded and analysed by a sleep technician in 30 s epochs in accordance with standard criteria (Berry et al., 2012).

4.2.4 Statistical analyses

Linear mixed models were constructed specifying; total sleep time (TST; min), sleep onset latency (min), light sleep (i.e., time spent in Stage N1 or Stage N2; min), deep sleep (i.e., time spent in Stage N3 sleep; min), REM sleep (time spent in Stage R sleep; min), wake after sleep onset (WASO; min), and sleep efficiency (i.e., total sleep time/time in bed x 100; %); as dependent variables. Fixed effects of condition and experimental night (main and interaction)

were specified with firefighter ID as a random effect. Post-hoc contrasts least significant differences (LSD) were specified between levels of the fixed effect factor (condition and experimental night). Uncorrected degrees of freedom are reported.

4.3 Results

Higher ambient temperature was not associated with any differences in sleep architecture compared to thermoneutral conditions (Table 4.1). Changes were seen across experimental nights of the simulation (Table 4.1; Figure 4.1 and Figure 4.2). Although the interaction effect of condition by experimental night was not significant on N1 (Table 4.1), post-hoc tests revealed minutes of N1 sleep in the *control* condition remained constant while in the *hot* condition N1 sleep was significantly reduced from baseline over experimental nights one and two (Figure 4.1). N2 sleep remained stable in both conditions over the duration of the experiment. N3 increased significantly in both conditions initially and remained different from baseline by experimental night three in the *control* condition. R sleep increased initially over experimental night one in the *hot* condition, then in both conditions over experimental nights two and three (Figure 4.1). Finally, SOL and WASO initially decreased, whilst TST and sleep efficiency increased in both conditions over experimental nights one and two before returning to near baseline levels by experimental night three (Figure 4.2).

Table 4.1 Results of linear mixed models analyses with condition and experimental night as fixed terms and participant ID as a random effect on measures of sleep quality and quantity.

	Condition			Experimental night			Condition by experimental night		
	F	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*
N1(min)	.96	1, 47	.333	5.14	3,126	**.002**	.84	3,126	.474
N2(min)	1.5	1,47	.225	3.03	3,127	**.032**	.54	3,127	.659
N3(min)	.051	1,46	.823	7.54	3,125	**.000**	1.01	3,125	.353
R(min)	1.65	1,44	.206	10.31	3,126	**.000**	1.30	3,126	.278
SOL(min)	.01	1,46	.931	13.61	3,127	**.000**	.25	3,127	.862
WASO(min)	.73	1,45	.398	6.05	1,126	**.001**	.34	3,126	.798
TST(min)	.938	1,46	.338	11.43	3,126	**.000**	1.24	3,126	.299
Sleep efficiency (%)	.322	1,46	.573	10.47	3,126	**.000**	.182	3,126	.908

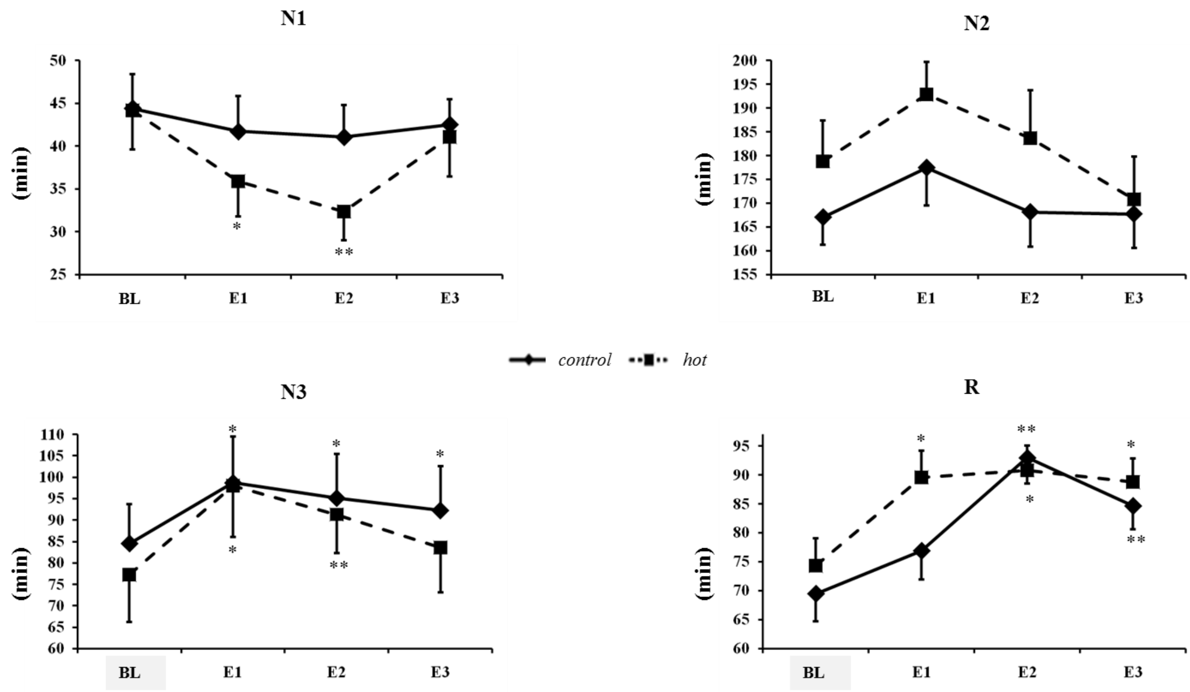

Figure 4.1 Sleep quantity. Comparison of minutes of N1, N2, N3, and R between the conditions over baseline (BL), experimental nights one, two and three (E1, E2, and E3).*(p<0.05), **(p≤0.001) indicates LSD post-hoc values were significantly different from BL. Bold lines represent the *control* condition and dotted lines represent the *hot* condition. Values expressed as mean ± standard error of the mean (SEM). Error bars represent SEM.

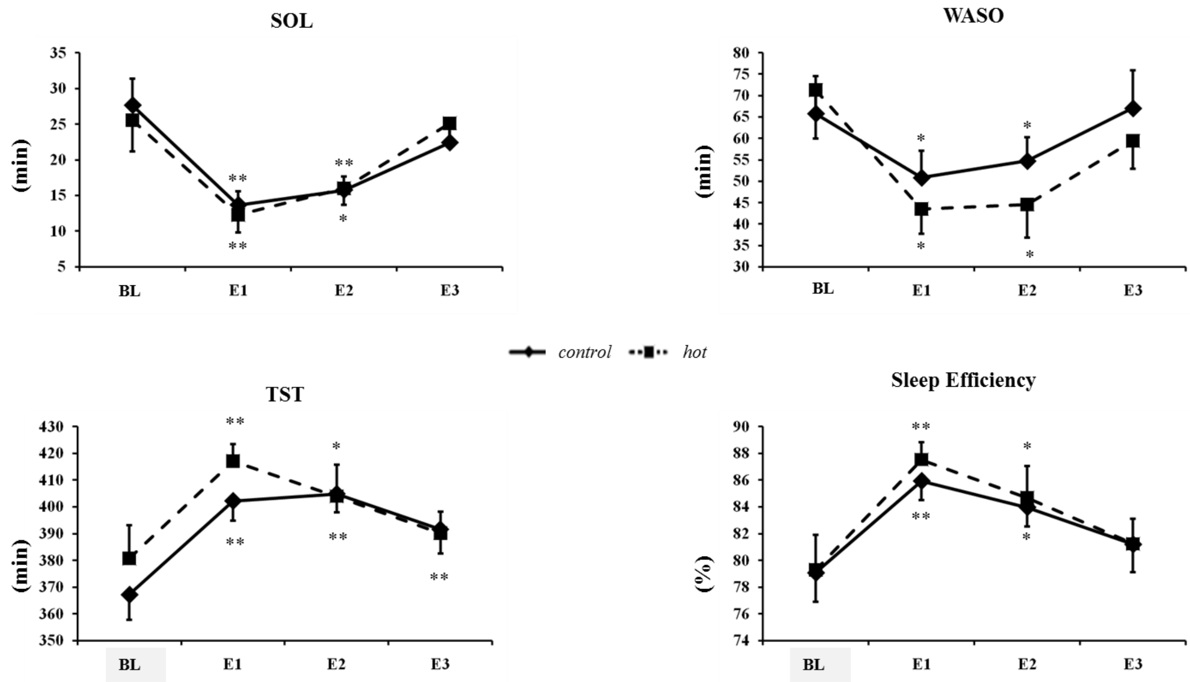

Figure 4.2 Sleep quality. Comparison of TST, SOL, WASO and Sleep Efficiency between the two conditions over BL, E1, E2 and E3.*($p \leq 0.05$), **($p \leq 0.001$) indicates LSD post-hoc values were significantly different from BL. Values represent mean ± SEM.

4.4 Discussion

The increasing amounts of N1 sleep revealed in the present study are in contrast to previous findings from brief (≤ 1 night) manipulations of ambient temperature showing decreases in the amount of Stage 1 sleep at low or high temperatures (Bach et al., 2002; Buguet et al., 1976; Libert et al., 1988). However, the consistent amounts of N2 in the present study compliment earlier findings revealing that amounts of Stage 2 sleep remain consistent during exposure to ambient temperature ranges of 18°C, 24°C, 29°C, 34°C, and 37°C (Haskell et al., 1981). The finding that N3 and R sleep increased in both conditions across experimental nights appears to contrast a robust finding from earlier reports of brief exposure studies that as temperature increases, SWS and REM sleep decrease (Haskell et al., 1981; Muzet et al., 1983; Muzet et al., 1984; Schmidt-Kessen & Kendel, 1973). However, it has also been found that provided with adequate bedtime clothing and covering, the microclimate established inside a bed will remain near constant at 29°C, whilst ambient temperature fluctuates from 16°C to 25°C (Muzet et al., 1984). This may also explain the results of the present study where participants were provided with adequate bedtime clothing and covering, hence the fluctuations in night-time ambient temperatures from 18-20°C or 23-25°C might not have been sufficient to alter the microclimate inside the bedding. In addition, a zone of thermoneutrality may have been achieved. As research descriptively defines this as the temperature range where sleep efficiency, TST, SWS, and REM sleep will be at their maximum, whilst WASO and SOL will be reduced. As shown in the present results especially for lower ambient night-time temperatures (Bach et al., 1994; Buguet, 2007; Haskell et al., 1981; Muzet et al., 1983).

The increase in N3 over nights in both conditions is also consistent with previous research focusing on daytime temperature manipulations. A series of studies (Horne & Moore, 1985; Horne & Porter, 1975; Horne & Staff, 1983) demonstrated that a high and sustained body heating for one to two hours with an associated rapid rise in core body temperature may trigger an increase in SWS, regardless of the method of induction. This is consistent with the

present findings as firefighters performed moderate bouts of self-paced physical activities during the day, which may have triggered a subsequent increase in N3 in the ensuing sleep episode in both conditions.

Finally, data from studies of more prolonged exposures to high or low ambient temperatures suggest the existence of an adaptive mechanism(s) protecting against sleep loss and modifications of sleep architecture (Buguet, 2007; Libert et al., 1988; Palca et al., 1986). The present results support not only the notion of a prolonged adaptation mechanism manifested as increasing N3 and R sleep, but also an initial adaptive mechanism in terms of increasing sleep quality, reflected in measures of SOL, WASO, TST, and sleep efficiency.

In conclusion, the present findings revealed that a simulated three-day, four-night wildland fireground deployment produced similar effects on sleep quality and quantity for firefighters in both cool and warm ambient day and night-time temperatures. In addition, increased TST, sleep efficiency, N3 and R sleep and reduced SOL and WASO, may indicate that the terms of thermoneutrality were satisfied in both conditions, or they fell either side of quadratic curve of thermoneutrality (Haskell et al., 1981), displaying similar deficits. Furthermore, the increases in N3 may be explained by an increased need for physical restitution (Horne & Moore, 1985; Horne & Porter, 1975; Horne & Staff, 1983) rather than as a sole effect of ambient temperature. Finally, the results of the present study suggest initial and potentially prolonged adaptations in the sleep of firefighters during multi-day wildfire campaigns.

Chapter 5: The Sleep Architecture of Australian Volunteer Firefighters During a Multi-day Simulated Wildfire Suppression: Impact of Sleep Restriction and Temperature

Peer-reviewed publication associated with this chapter (Appendix I)

Cvirn, M. A., Dorrian, J., Smith, B. P., Jay, S. M., Vincent, G. E., & Ferguson, S. A. (2017). The sleep architecture of Australian volunteer firefighters during a multi-day simulated wildfire suppression: Impact of sleep restriction and temperature. *Accident Analysis & Prevention, 99*, 389-394. doi: https://doi.org/10.1016/j.aap.2015.11.013

Nature of Candidate's Contribution, including percentage of total: 85%
Writing and results of the publication.
Nature of all Co-Authors' Contributions, including percentage of total: 15%
Dorrian, J. (Results 5%), Ferguson, S. A. (Writing/editing 3.5%), Jay, S. M. (Writing/editing 2%), Smith, B. P. (Writing/editing 3%), & Vincent, G. (Results 1.5%).

Has this paper been submitted for an award by another research degree candidate (Co-Author), either at CQUniversity or elsewhere? No.

Candidate's declaration

I declare that the publication above meets the requirements to be included in the thesis as outlined in the Research Higher Degree Theses Policy and Procedure

Cvirn, MA	April 2018
(Original signature of Candidate)	Date

Abstract

Wildland firefighting exposes personnel to combinations of occupational and environmental stressors that include physical activity, heat and sleep restriction. However, the effects of these stressors on sleep have rarely been studied in the laboratory, and direct comparisons to field scenarios remain problematic. The aim of this study was to examine firefighters' sleep during a three-day, four-night simulated wildfire suppression that included sleep restriction and physical activity/work circuits representative of firefighting wildfire suppression tasks, in varied temperatures. Sixty-one volunteer firefighters (37.5 ± 14.5 years of age, mean ± SD) were assigned to one of three conditions: *control* (n = 25; 8 h sleep opportunities and 18-20°C), *awake* (n = 25; 4 h sleep opportunities and 18-20°C) or *awake/hot* (n = 11; 4 h sleep opportunities and 33-35°C during the day and 23-25°C during the night). Results demonstrated that amounts of N1, N2 and R sleep, TST, SOL and WASO declined, whilst sleep efficiency increased significantly in the *awake* and *awake/hot* conditions compared to the *control* condition. Results also demonstrated that N3 sleep remained relatively stable in the *awake* and *awake/hot* conditions compared to *control* values. Most importantly, no significant differences were found for any of the sleep measures between the *awake* and *awake/hot* conditions. Thus, working in hot daytime temperatures in combination with sleep restriction during the night did not affect patterns of sleep compared to working in temperate conditions in combination with sleep restriction during the night. However, the effects on sleep of hotter (> 25°C) night-time temperatures with the addition of sleep restriction and physical activity remains to be studied.

5.1 Introduction

Firefighting exposes personnel to combinations of occupational and environmental stressors including sleep restriction (Cater et al., 2007), long shifts of variable intensity physical activity (Cuddy et al., 2007; Phillips et al., 2012), and environmental extremes (Aisbett et al., 2012). Australian wild fires are known for hot temperatures (> 45°C; Cheney, 1976), and require firefighters to work extended periods (up to 16 h per shift; Cater et al., 2007; Phillips et al., 2012) in deployments that can last for days to weeks (Hunter, 2003; Rodriguez-Marroyo et al., 2012). As a result, cumulative sleep loss can occur, with firefighters reporting on average 3 h to 6 h sleep per night during multi-day fire deployments (Cater et al., 2007; Gaskill & Ruby, 2004). Inadequate sleep has implications for performance and places individuals at increased risk of error and incident (Åkerstedt & Wright, 2009). Although data on Australian firefighters' sleep patterns are sparse, laboratory and military studies focusing on the individual and combined effects on sleep architecture of physical activity, sleep restriction and/or ambient temperatures provide some insight.

Laboratory studies on the effects of exercise on sleep reveal consistent increases in SWS (Horne & Porter, 1975; Horne & Staff, 1983), and in some cases associated reductions in REM sleep (Horne & Moore, 1985) if exercise is conducted late in the afternoon and without a sufficient daytime recovery period. The effects of sleep restriction on sleep architecture are also well established, with declines in amounts of Stage 1, 2, and REM sleep, and a conservation of SWS from sleep doses of 3-6 h per night for 7-14 consecutive days (Belenky et al., 2003; Van Dongen, Maislin, et al., 2003). However, the effects of varying ambient temperatures on sleep patterns are less clear.

Research using temperatures between 21°C-37°C (Haskell et al., 1981) demonstrated that cold, rather than warm temperatures were generally more disruptive to sleep. Specifically, increases in Stage 1 sleep and decreases in Stage 2 and REM sleep were reported with 21°C the most disruptive temperature. In contrast, no significant effects on the total duration of REM sleep or latency were reported during two consecutive nights sleep at temperatures of 13°C, 16°C, 19°C, 22°C, or 25° C (Muzet et al., 1983). The effects on sleep during sleep restriction in cool and warm temperatures have also been examined.

Sleep restriction to 4 h for four nights at 20°C or 35°C was associated with decreased amounts of Stage 1 sleep and wake after sleep onset (Bach et al., 1994). Duration of Stage 4 sleep increased over nights of sleep restriction at 20°C but not 35°C. Similar military research combining the effects of 4 h sleep restriction for 6 nights with an initial 90 h total sleep deprivation period, during a tactical defence exercise in cold winter temperatures, revealed Stage 2 sleep decreased whilst all other stages remained constant (Haslam, 1982).

Laboratory and field studies provide insight into the effects on sleep architecture of single or dual stressor combinations of physical activity, sleep restriction, and/or ambient temperatures however the combination of all three has not been studied in the laboratory. Field research is available on combinations of stressors similar to firefighting (i.e., physical activity, sleep restriction and environmental extremes), such as in military operations (Haslam, 1982; Lieberman, Bathalon, Falco, Kramer, et al., 2005). However, direct comparisons are limited because such studies typically include periods of TSD at the beginning of experimental trials, in addition to limited control of extraneous variables, such as fluctuations in natural weather conditions (Haslam, 1982; Lieberman, Bathalon, Falco, Kramer, et al., 2005).

The aim of this study was to determine whether changes in sleep architecture from sleep restriction in combination with heat and physical activity are significantly different from those of sleep restriction and physical activity alone, and if these conditions differ from full sleep opportunities during multi-day simulated wildfire suppression.

5.2 Methods

5.2.1 Participants

Participants were active volunteers recruited from the South Australian Country Fire Service, Country Fire Authority (Victoria), Tasmania Fire Service, New South Wales National Parks and Wildlife Service, and Australian Capital Territory Fire and Rescue. In groups of up to five, participants took part in a multi-day simulated wildfire suppression. Participants were pre-screened for any current medical conditions or use of medicines, such as hormonal therapy, and for females menstrual phase and menopausal status was documented in the General Health Questionnaire. Participants were assigned to one of three conditions. The

control condition consisted of 25 participants (3 f, 22 m; mean = 36.7 y, SD = 15.9 y), with a mean BMI of 27.0 kg/m² (SD = 4.8 kg/m²). The *awake* condition consisted of 25 participants (5 f, 20 m; mean = 38.5 y, SD = 13.2 y) with a BMI of 29.2 kg/m² (SD = 4.9 kg/m²). The *awake/hot* condition consisted of 11 participants (1 f, 10 m; mean = 37.5 y, SD = 15.6 y) with a BMI of 26.7 kg/m² (SD = 4.6 kg/m²). Power analyses indicated that a total sample size of 75 participants (across three groups) would be required ($\alpha = 0.05$, $1-\beta = 0.80$), using an estimated effect size of $f = 0.16$ from previous research investigating changes in REM sleep and SWS with ambient temperature changes of 3°C (Muzet et al., 1983; Muzet et al., 1984). However, due to operational time constraints only 11/25 participants could be collected for the *awake/hot* group resulting in a total sample of 61 participants. This yielded an achieved study power of 0.71. Ethics approval was obtained from the CQUniversity (H12/01-016) and Deakin University Human Research Ethics Committees (2010-170).

5.2.2 Procedure

The three-day, four-night multi-day simulated wildfire suppression consisted of a baseline night with an 8 h sleep opportunity (TIB 22:30-06:30 h), followed by two experimental nights with either 8 h or 4 h sleep opportunities (TIB 22:00-06:00 h or 02:00-06:00 h) for the *control* or *awake* and *awake/hot* conditions, respectively. The fourth night was a recovery sleep with all conditions provided with an 8 h sleep opportunity (TIB 22:00-06:00 h). For the *control* and *awake* conditions, day- and night-time temperatures remained between 18-20°C throughout the protocol. From 11:30 h on baseline day, temperature in the *awake/hot* condition was set to 33-35°C during the day (06:00-18:00 h), and 23-25°C during the two experimental nights and recovery (18:00-06:00 h). Temperature was monitored using a wireless temperature and humidity logger (HOBO ZW_003, One Temp Pty Ltd, Australia), data receiver (HOBO ZW_RCVR, One Temp Pty Ltd, Australia), and associated software (HOBO Pro Software, One Temp Pty Ltd, Australia). During the simulated dayshift firefighters performed physical work and cognitive testing sessions, three to five per day. Each 2 h session consisted of; 55 minutes of physical work with wildland firefighter suppression tasks (for a detailed methodology and the effects of sleep restriction on physical task performance the reader is referred to Vincent et al., 2015); 20-25 minutes of physiological testing (for a detailed methodology and the effects of heat on physiology and work performance the reader is referred to Larsen, Snow, Vincent, et al., 2015); 20-25

minutes of cognitive testing (reported in Chapter 6, Section 6.2 and Chapter 7, Section 7.2); and a 15-20 minute rest period.

5.2.3 Activity data

Actiwatch-64 (Mini-Mitter Philips Respironics, Bend, OR) or Actical Z-series (Mini-Mitter Philips Respironics, Inc.) devices were worn on the either the dominant or non-dominant wrist, prior to and during the experiment. Both activity monitors contain an omnidirectional piezoelectric accelerometer sampling movement at 32 Hz. Data collected with the Actical and Actiwatch (Mini Mitter Co., Inc., Bend, OR) correlated strongly with activity energy expenditure (AEE) and physical activity ratio (PAR; Puyau, Adolph, Vohra, Zakeri, & Butte, 2004). The outputs from both accelerometers were also highly correlated ($r = 0.93$). As such, both activity monitors provide valid measures of AEE and PAR and can be used to discriminate sedentary, light, moderate and vigorous levels of physical activity.

5.2.4 Polysomnography

Sleep was recorded using the Siesta Portable EEG system (Compumedics, Melbourne, Victoria, Australia). A standard montage of electrodes was applied; two channels of EEG (C4-M1, C3-M2); left and right outer canthi electro-oculograms (LOC, ROC; EOG); and two channels of chin electromyography. One and a half hours prior to bedtime each participant had polysomnography Grass™ gold-cup electrodes (Astro-Med, Inc., West Warwick, RI) applied to their face and scalp. All sleep records were blinded and analysed by a sleep technician in 30 second epochs in accordance with standard criteria (Iber et al., 2007).

5.2.5 Sleeping conditions

Participants slept in individual beds located in a single room. with five participants or less to a single room. Signals from each portable siesta transmitted wirelessly to designated participant laptops located in a separate room monitored overnight by a sleep technician. Ten minutes prior to scheduled bedtimes all sleep and monitoring equipment was placed in position and participants made themselves comfortable prior to lights out. Participants were provided with an electronic pager should they need assistance throughout the night and were

awoken in the morning at the scheduled times with assistance from researchers to remove the monitoring equipment. For each sleep opportunity participants were provided with camping stretchers, inflatable mattresses, and sleeping bags with accompanying pillows and linen to simulate fireground conditions.

5.2.6 Measures and statistical analyses

Physical activity was measured by averaging the activity counts for each 60 second epoch over the 16 h period (06:00 h to 22:00 h) preceding each sleep episode. To assess differences in physical activity a preliminary mixed model analysis of variance was conducted with 2 fixed factors of condition (3 levels – *control*, *awake*, and *awake/hot*) and experimental night (4 levels – baseline, experimental night one, experimental night two and recovery) and a random factor of participants (n = 61). Results revealed significant differences in physical activity between conditions over experimental nights (see Section 4.3.1). Since physical activity changed differentially across conditions, it was specified as a covariate in the models for sleep parameters. Models were run without, then with the covariate with optimal model fit for each sleep variable assessed by comparing Akaike weights between candidate models (Burnham & Anderson, 2002). The denominator degree freedoms for F statistics were computed using the Satterthwaite approximation method. Uncorrected degrees of freedom are reported. LSD post-hoc contrasts were specified between levels of the fixed effect factors.

For each sleep period, the following dependent variables were calculated: light sleep (i.e., time spent in Stage N1 or Stage N2 sleep; min), deep sleep (i.e., time spent in Stage N3 sleep; min), REM sleep (time spent in Stage R sleep; min), total sleep time (h), sleep onset latency (min), WASO (min), and sleep efficiency (calculated by total sleep time/time in bed x 100; %). To assess the main effects of condition and experimental night and the interaction effect of condition by experimental night on sleep dependent variables, data were analysed using a mixed model analysis of variance with 2 fixed factors of condition (3 levels) and experimental night (4 levels) and a random factor of participants (n = 61) with physical activity as a co-variate. All statistical analyses were conducted using SPSS 20.0.

5.3 Results

5.3.1 Physical activity

Significant main effects on physical activity were found for condition ($F_{2,71}$=4.37, $p<0.05$) and experimental night ($F_{3,174}$=23.99, $p<0.001$). There was also a significant interaction effect of condition by experimental night on physical activity ($F_{6,174}$=2.76, p=0.01). Post-hocs revealed significantly higher physical activity in the *awake* condition compared to the *control* and *awake/hot* conditions, on experimental night two ($p<0.01$ and p=0.01, respectively) and the recovery night ($p<0.01$ and p=0.01, respectively).

5.3.2 Sleep architecture and quantity

Physical activity was not a significant covariate in any of the models and did not change the effects of the experimental manipulation on any sleep parameters with the exception of SOL (Table 5.1). There were significant main effects of condition on every sleep measure, although a non-significant reduction ofN3 (Table 5.1). There were also significant main effects of experimental night on all sleep measures, and interaction effects of condition by experimental night for all sleep variables, except SOL (Table 5.1). Figure 5.1 shows sleep architecture/patterns for each of the stages of sleep in minutes. Stage N1 sleep decreased significantly by experimental night two, whilst N2 and R sleep significantly decreased over experimental nights one and two, in both the *awake* and *awake/hot* conditions compared to the *control* condition (Figure 5.1). N3 sleep remained relatively stable over experimental nights in both the *awake* and *awake/hot* conditions with no significant differences compared to the *control* condition, except for on experimental night one between the *control* and *awake* conditions (Figure 5.1).

Figure 5.2 shows measures of sleep quantity. TST and WASO significantly decreased over experimental nights one and two in both the *awake* and *awake/hot* conditions compared to *control* and WASO was still significantly shorter by recovery in the *awake* condition compared to the *control* (Figure 5.2). SOL was significantly shorter, whilst sleep efficiency was significantly longer, in the *awake* and *awake/hot* conditions compared to *control* by experimental night two, and into recovery for SOL (Figure 5.2).

Table 5.1 Results of mixed-effect ANOVAs with physical activity (co-variate), condition and experimental night as fixed terms and participant as a random effect on measures of sleep architecture and quantity.

	Physical activity			Condition			Experimental night			Condition by night		
	F	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*
N1(min)	1.78	1,150	.184	3.21	2,60	**.047**	12.42	3,165	**<.001**	2.36	6,157	**.033**
N2(min)	1.56	1,163	.213	15.19	2,60	**<.001**	80.38	3,164	**<.001**	23.80	6,155	**<.001**
N3(min)	1.95	1,211	.164	0.31	2,67	.732	10.96	3,158	**<.001**	4.45	6,152	**<.001**
R(min)	1.24	1,142	.268	12.63	2,62	**<.001**	30.13	3,166	**<.001**	14.39	6,158	**<.001**
TST(h)	3.67	1,128	.057	42.59	2,58	**<.001**	110.06	3,165	**<.001**	40.75	6,157	**<.001**
SOL(min)	4.48	1,119	**.036**	4.39	2,60	**.017**	25.37	3,168	**<.001**	2.04	6,161	.064
WASO(min)	2.28	1,176	.133	7.39	2,64	**.001**	25.19	3,165	**<.001**	3.18	6,157	**.006**
Efficiency(%)	1.78	1,150	.184	3.21	2,60	**.047**	12.42	3,165	**<.001**	2.36	6,157	**.033**

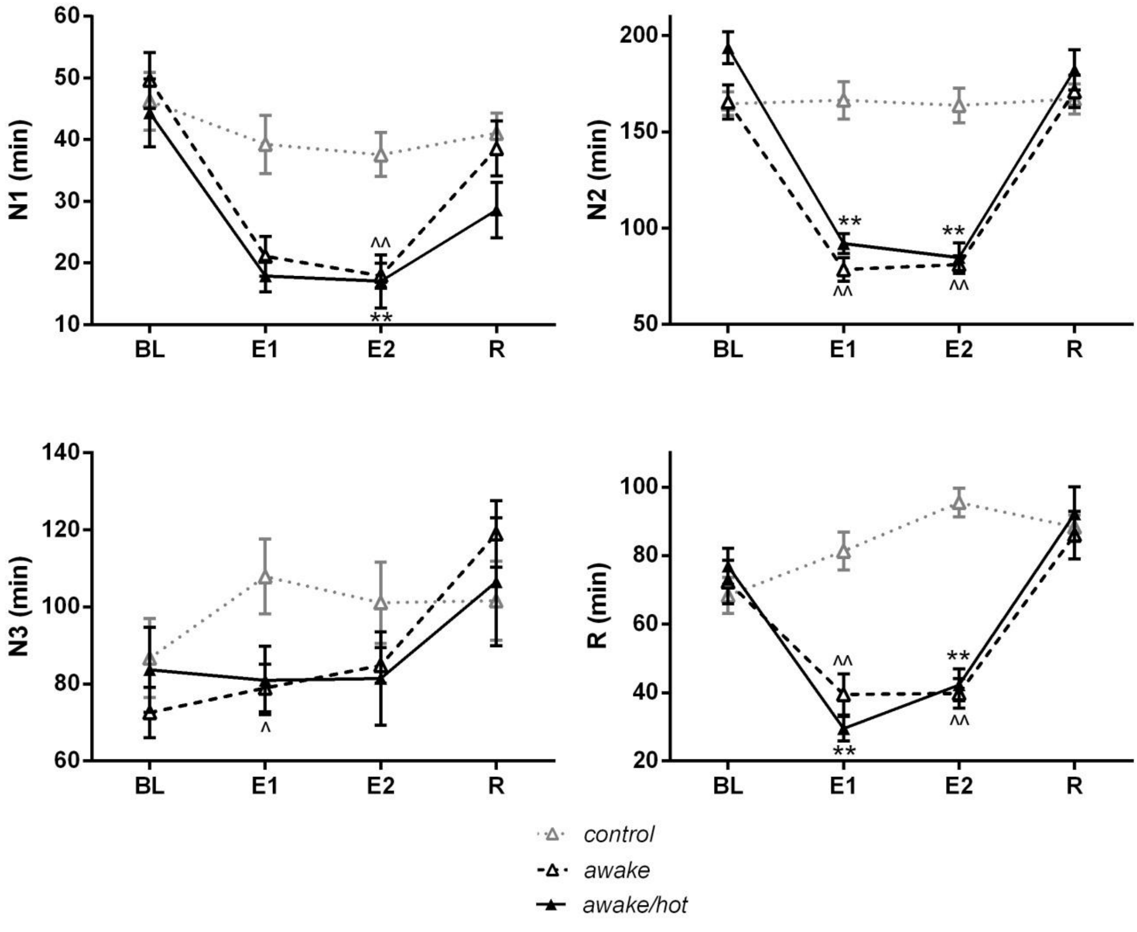

Figure 5.1 Sleep architecture. Comparison of sleep Stages N1, N2, N3, and R between the three conditions over baseline (BL), experimental nights one and two (E1, E2), and recovery

(R). **(p<0.01) indicates *awake/hot* condition values were significantly different from the *control* condition. ^(p<0.05), ^^(p<0.01) indicates *awake* condition values were significantly different from the *control* condition. Values expressed as mean ± SEM.

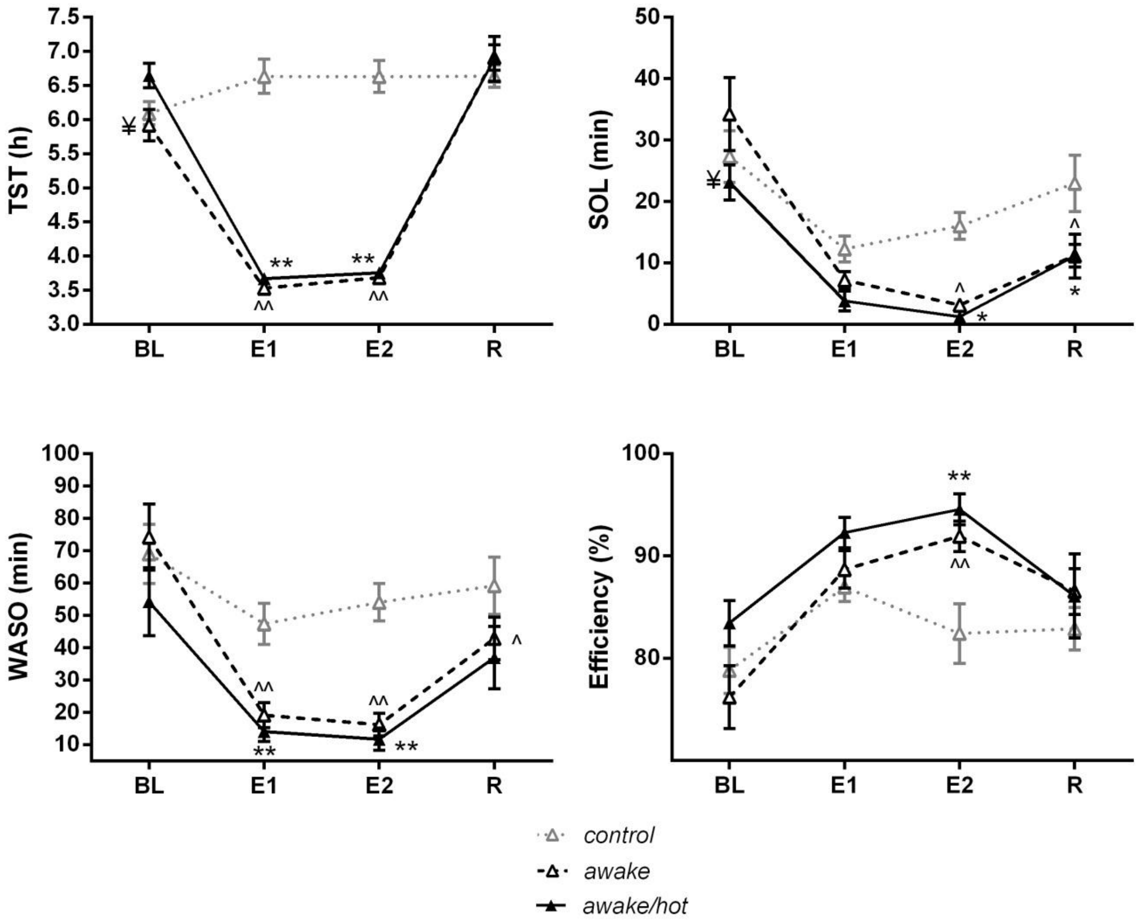

Figure 5.2 Sleep quantity. Comparison of TST, SOL, WASO and Efficiency between the three conditions over BL, E1, E2 and R. *(p<0.05), **(p<0.01), indicates *awake/hot* condition values were significantly different from the *control* condition. ^(p<0.05), ^^(p<0.01), indicates *awake* condition values were significantly different from the *control* condition. ¥ indicates *awake/hot* condition values were significantly different from the *awake* condition (p<0.05). Values expressed as mean ± SEM.

5.4 Discussion

This study examined the effects on firefighters' sleep of a three-day four-night simulated wildfire suppression. The novel simulation involved sleep restriction or full sleep

opportunities and physical activity in thermoneutral and hot temperatures. The findings suggest that there are no differences in sleep architecture or sleep quantity during a 4 h sleep opportunity in either warm or cool day- and night-time temperatures. Although as shown by previous research sleep quality and quantity is impaired with sleep restriction to 4 h, for four nights under extremely hot (35°C) temperatures (Bach et al., 1994). With findings from this research suggesting that the addition of heat to sleep restriction, has a suppressive effect on Stage 4 sleep increases induced by sleep restriction alone (Bach et al., 1994). There were however, significant differences between both sleep restriction conditions and the *control* condition, provided with an 8 h sleep opportunity in thermoneutral temperatures. That is, amounts N1, N2 and R sleep, TST, SOL and WASO declined, whilst efficiency was higher in the *control* condition compared to the *awake* and *awake/hot* conditions on the second night of sleep restriction. In addition, N3 sleep remained relatively stable over the two consecutive nights of sleep restriction and recovery in the *awake* and *awake/hot* conditions compared to *control* values. The only exception was reduced N3 in the *awake* condition on the first sleep restriction night compared to the *control* condition. These results are consistent with previous seminal studies on chronic sleep restriction demonstrating SWS is relatively conserved whilst Stage 1, 2 and REM sleep decline relative to the amount of sleep restriction (Belenky et al., 2003; Van Dongen, Maislin, et al., 2003).

In the current study, performing physical work in high 33-35°C daytime temperatures did not impact on sleep beyond the effects of sleep restriction alone. This was surprising given a series of studies reporting that high and sustained body heating for 1-2 hours in the afternoon, without sleep restriction and also under temperatures comparable to the current study, may trigger an increase in SWS regardless of the method of induction. That is, passive heating (Horne & Staff, 1983), 41 °C warm temperature baths (Horne & Reid, 1985), or intense exercise (Horne & Porter, 1975). Similarly, the finding that N3 (Stage 3 and Stage 4 sleep combined) remained stable during sleep restriction at 18-20°C contrasts the results of a previous sleep restriction study (Bach et al., 1994). Reporting that sleep restriction to 4 h for four consecutive nights in 20°C was associated with a significant increase in Stage 4 sleep compared to full 8 h rest opportunities (Bach et al., 1994).

Similarly, it would appear that sleep restriction in mild, slightly elevated night-time compared to thermoneutral night-time temperatures, does not adversely affect sleep architecture and quantity. This may mean that there is a possibility that sleep restriction masked temperature

induced changes, since previous research has found the addition of heat may suppress increases in Stage 4 sleep induced by sleep restriction by itself (Bach et al., 1994). Nonetheless, this result is consistent with our previous study (Chapter 4) reporting no significant differences in sleep patterns between warm (33-35°C) and thermoneutral (18-20°C) temperatures with 8 h rest opportunities (Cvirn, Smith, Jay, Vincent, & Ferguson, 2015). Consistent with previous research no significant changes in sleep stages, with the exception of N2 in this study, have been demonstrated for five consecutive nights sleep at 21°C compared with five nights at a thermoneutral temperature of 29°C (Palca et al., 1986). Similarly, no differences in amounts of REM sleep were reported from two nights sleep at temperatures of 13°C, 16°C, 19°C, 22°C, or 25°C (Muzet et al., 1983).

These findings contrast research (Haskell et al., 1981) showing that cold temperatures (defined as 21°C and 24°C) were associated with increased amounts of Stage 1 sleep, WASO and reduced amounts of Stage 2 and REM sleep, compared to a thermoneutral (29°C) temperature. Although in the present study reduced amounts of N2 and R sleep were seen in both the *awake* and *awake/hot* conditions, the two temperature conditions did not significantly differ in relation to one another on N2 or R sleep. The decrease is therefore more likely due to sleep restriction rather than the experimental temperature manipulation. It should be noted however, that in protocols such as this one and Muzet et al. (1983) where bedding (i.e., sheets and blanket) is provided, the thermoneutral temperature is approximately 19°C (18-20°C). However, if participants are required to sleep semi-naked (i.e., in shorts), as in the research by Haskell et al. (1981) and Palca et al. (1986), then the thermoneutral temperature may be higher, around 29°C. This is due to the finding that with adequate bedtime clothing and covering, the microclimate inside a bed will remain near constant at 29°C, while ambient temperature can be as low as 16°C (Muzet et al., 1984).

It is possible that night-time temperatures in the range of 18-20°C or 23-25°C are too mild to affect night-time sleep. The suggestion that elevated night-time temperatures may be more disruptive to sleep is also consistent with previous research showing increases in WASO and decreases in SWS sleep following ambient temperature increases from 26°C to 32°C during the second half of the sleep (Okamoto-Mizuno, Tsuzuki, Mizuno, & Iwaki, 2005). Similarly, lower amounts of Stage 1 and REM sleep, SWS and TST with an increased number and duration of awakenings have been reported with the use of high electric blanket temperatures during the night (Karacan, Thornby, Anch, Williams, & Perkins, 1978).

Uneven participant numbers between conditions may have contributed to the pre-existing differences at baseline, where significantly increased SOL in the *awake* condition resulted in significantly decreased TST, compared to the *awake*/hot and *control* conditions. This might also explain why there were no significant pre-existing differences on the baseline night for any sleep measures between the *awake* and *control* conditions where participant numbers were even. Additionally, PSG changes in relation to the types of stressors (i.e., physical activity, temperature, and sleep restriction) presented in the laboratory may not reflect levels found in real wildfire suppression. Further, it should also be noted that another limitation is that since sleep restriction is combined with physical activity, it is not possible to disentangle the specific effect of exercise and heat on sleep architecture and thereby extension cognitive function. Also, since participants slept in a single room with five or less people in one room at a time, there is the possibility that sleep was affected by other participants' awakenings, such as when going to the bathroom during the night. Also as the study was slightly underpowered the findings of no differences between the sleep restriction temperature conditions should be interpreted carefully due to lower participant numbers in the *awake/hot* condition. Additionally, physical activity was a significant covariate for SOL and was associated with a significant decrease in SOL on the second night of sleep restriction and recovery for the *awake* and *awake/hot* conditions compared to *control* values. However, preliminary analyses revealed only the *awake* condition, not the *awake/hot* condition was significantly higher in physical activity compared to the *control* condition over these nights. Hence, the potential for an inverse relationship to exist with increases in physical activity associated with decreases in SOL cannot be substantiated by our findings. However, such an inverse relationship has been reported in a previous meta-analysis on the effects of acute and chronic exercise on sleep (Kubitz, Landers, Petruzzello, & Han, 1996).

This study provides the first comprehensive simulated investigation into the sleep architecture of wildland firefighters during sleep restriction and elevated temperatures. The findings indicate that the effect of sleep restriction is more detrimental to firefighters' sleep than heat. The effect of higher ambient temperatures at night remains to be studied given the increase in this study was mild from 18-20°C to 23-25°C. Future research is needed to consider the impact of high night-time ambient temperatures (> 25°C) on sleep architecture in combination with other stressors such as day-time physical activity and sleep restriction.

Chapter 6: The Effects of Hydration on Cognitive Performance During a Simulated Wildfire Suppression Shift in Temperate and Hot Conditions

Abstract

The effects on dehydration and cognitive performance from passive heat and/or physical activity are well established in the laboratory. However, previous research has not determined the effect on cognitive performance of hydration, thermoneutral and hot temperatures in the presence of physical activity. Personnel working in occupations such as wildland firefighting are often exposed to such conditions. This study aimed to investigate the effects of temperature and dehydration on cognitive performance during a simulated wildfire suppression shift. Seventy-three volunteer firefighters (35.7 ± 13.7 years, mean ± SD) participated in a simulation of a wildfire suppression tour in either *control* (i.e., temperate or thermoneutral) (n = 45) or *hot* conditions (n = 28). During the simulation, participants completed three physical work circuits involving repeated bouts of self-paced physical work activities based on real wildfire suppression duties. Each physical work circuit was followed with a cognitive test battery and hydration measurement using urine specific gravity (U_{sg}) analyses. Temperatures were set between 23-25°C for the *control* condition and 33-35°C for the *hot* condition. Cognitive performance was measured using the psychomotor vigilance task and the Stroop task. Performance declined on measures of PVT when participants were *approaching dehydration* and in the heat, whilst for Stroop RT on non-matching word-pairs, performance was impaired when *approaching dehydration* late in the afternoon, irrespective of external temperature conditions. Firefighters may be most at risk of deterioration of simple mental functions in the heat whilst *approaching dehydration*, however may be at risk of complex mental impairment if *approaching dehydration* late in the day (i.e., 18:00 h), irrespective of the environmental temperature. These results may also be influenced by a circadian dip in core body temperature in the afternoon and evening associated with a decline in performance. Other factors that may influence performance remain to be determined by future research such as age, sex, and chronotype.

6.1 Introduction

Wildland fires are known for extreme heat, low humidity and high wind speeds (Aisbett et al., 2012). In order to suppress wildfires, firefighters often work shifts of up to 16 hours (Cuddy et al., 2007; Gaskill & Ruby, 2004). Performing physically demanding manual handing tasks (Phillips et al., 2012) in temperatures as high as 46.4°C (Teague et al., 2010), while wearing heat retaining personal protective clothing and equipment (Barr et al., 2010). However, not all firefighting operations are conducted in extreme temperatures. For example, during the February 2009 fires in Victoria, Australia, suppression and blacking out activities were ongoing in temperatures as low as 15.8°C (Raines et al., 2012). Given the variation in the ranges of ambient temperatures firefighters are exposed to during wildfire suppression (Raines et al., 2012) the effects of temperature on firefighters' health and safety is an important consideration for fire agencies. Examining firefighters' mental performance whilst performing physical work in different ambient environments could directly inform agencies' decisions in relation to the productivity and safety of their crews. Further, such information could lead to customised safety procedures (e.g., rest breaks and fluid provisions) for different ambient temperatures. Also, this knowledge could be used to strengthen existing protocols or policies.

However, performance may not only be affected directly by ambient temperature, but also dehydration, which in turn is affected by the ambient environment. Previous research (Hendrie et al., 1997; Raines et al., 2015; Raines et al., 2012, 2013) has identified that wildfire suppression can lead to dehydration in Australian wildland firefighters, although cognitive performance has not yet been examined. For fire agencies striving to implement safety controls it is important to determine the risks to firefighters' cognitive function and therefore safety when exposed to ambient temperature, physical activity, and dehydration, or a combination (Cuddy et al., 2008; Hendrie et al., 1997; Raines et al., 2012, 2013; Ruby et al., 2003).

While the effects on cognitive performance of exercise in more cooler or temperate conditions with dehydration have been well documented in the laboratory in healthy young norms, studies show disparate results. In temperatures of 20-21°C, regardless of body mass (B_m) losses of 2.2% and 4.1%, in fluid and no fluid exercise conditions, cognitive

performance did not vary as a function of hydration status (Grego et al., 2005). In contrast other research showed dehydration in the range of 1-2% B_m loss from exercise in temperate conditions degraded cognitive performance, compared to exercise whilst maintaining euhydration (Ganio et al., 2011). Hence, it would seem clear that it is not the effect of exercise itself, but rather dehydration that affects cognitive performance. Similarly, the effects of dehydration induced via exercise or passive heat alone to 2.8% of B_m have shown comparable cognitive performance impairments compared to hydrated individuals (Cian et al., 2001; Cian et al., 2000).

Further, results from studies on the effects of heat and exercise induced dehydration on cognitive performance also show inconsistencies. Studies have reported dehydration losses of 2-4% B_m in ambient heat with physical activity were associated with cognitive performance impairments (Gopinathan et al., 1988; Sharma et al., 1986). In contrast other research demonstrated B_m losses of < 2% from exercise in the heat were associated with no differences in cognitive performance compared to hydrated controls (Serwah & Marino, 2006). Similarly, no effects on cognitive performance have been reported from B_w losses of up to 3.7% from exercise in a heated chamber in conditions with and without fluid replacement (Tomporowski et al., 2007). Hence, collectively these studies on the effects of heat and exercise induced dehydration on cognitive performance show different results, reporting either impairments (Gopinathan et al., 1988; Sharma et al., 1986), or no change (Serwah & Marino, 2006; Tomporowski et al., 2007).

To the authors' knowledge, there is no existing laboratory (or field) research utilising a protocol comparing both cool and hot variations in external temperatures simultaneously with physical activity and dehydration to determine the effects on cognitive performance. Hence the effects of working physically demanding jobs in the heat, or in milder temperatures while being either hydrated or dehydrated on mental work capacity, for firefighters or other populations, is still unknown. For fire agencies aiming to put in place occupational health and safety controls it is important to understand if mental functioning declines with hydration status. To ensure ecological validity, these effects are usually studied in the field, however as temperature, wind, and the severity of the emergency situations are all highly variable it is not feasible to use field data to isolate the effect of specific temperatures during manual handling physical activities on cognitive performance. Therefore, the purpose of the present study was to conduct a wildfire suppression laboratory simulation in hot and thermoneutral

ambient temperatures to determine the effect of resulting hydration levels on cognitive performance.

6.2 Methods

6.2.1 Participants

Participants (*n* = 73, 62 m, 11 f; age = 35.7 ± 13.7 y; BMI = 27.8 ± 4.5 kg/m^2) were recruited from the Country Fire Service, Country Fire Authority, Tasmania Fire Service, New South Wales National Parks and Wildlife Service, and Australian Capital Territory Fire and Rescue. These demographics were fairly representative of Australian wildfire volunteer firefighters, for example, a 2005 survey of Country Fire Authority first year volunteers showed an average age of 39.2 y (SD = 14.36 y; McLennan & Birch, 2005). Firefighters participated in a wildland fireground deployment simulation and were assigned to one of two conditions ─ either *control* or *hot* (characteristics reported in Table 6.1). Ethics approval was obtained from the CQUniversity (H12/01-016) and Deakin University Human Research Ethics Committees (2010-170).

Table 6.1 Demographics of firefighters in the *control* and *hot* conditions. Values are in mean ± SD.

	control	*hot*
n	45	28
Age (y)	36.4 ± 14.2	34.7 ± 13.2
BMI (kg·m^{-2})	28.3 ± 4.8	26.9 ± 4.0
Male:Female	38:7	24:4

6.2.2 Procedure

Participants arrived at 19:00-20:00 h on the baseline night and completed numerous familiarisation trials on the cognitive tasks to eliminate any potential practice effects. Participants were then provided with an 8 h sleep opportunity from 22:30-06:30 h. In the morning from 08:15-10:30 h participants completed further cognitive task familiarisation and the experimental protocol was initiated at 11:30 h, where the climate controlled laboratory

temperature either remained constant between 23-25°C for the *control* condition or was increased to 33-35°C, for the *hot* condition. Temperature was monitored using a wireless temperature and humidity logger (HOBO ZW_003, One Temp Pty Ltd, Australia), data receiver (HOBO ZW_RCVR, One Temp Pty Ltd, Australia), and associated software (HOBO Pro Software, One Temp Pty Ltd, Australia). The simulated fireground shift commenced at 12:30 h and consisted of three two hourly sessions comprised of physical work, and physiological and cognitive testing from 12:30-14:30 h, 14:30-16:30 h, and 16:30-18:30 h. Each session was comprised of a 55 minute physical work circuit involving wildland firefighter suppression tasks (for a detailed methodology and the effects of sleep restriction on physical work the reader is referred to Vincent et al., 2015), 20-25 minutes of physiological testing (for a detailed methodology and the effects of simulated firefighting and physiology under very hot conditions the reader is referred to Larsen, Snow, Williams-Bell, & Aisbett, 2015), and 20-25 minutes of cognitive testing followed by a 15-20 minute rest period. For the PVT and Stroop task the trials were conducted at the same overlapping times each day 13:50 h (early-afternoon trial), 15:50 h (mid-afternoon trial) and 17:50 h (late-afternoon trial).

6.2.3 Cognitive performance measures

6.2.3.1 Psychomotor Vigilance Task

Cognitive performance was measured using the psychomotor vigilance task (Dinges & Powell, 1985). The PVT specifically provides an automatic measure of sustained attention (Dorrian, Dinges, & Rogers, 2005). The PVT was tailored for use on a personal digital assistant by the Walter Reed Army Institute (Thorne et al., 2005). A validated five minute PDA substitute version of the PVT was presented on the Tungsten E PalmPilot (Palm Inc., Sunnyvale, California; Lamond, Dawson, & Roach, 2005; Lamond et al., 2008; Roach, Dawson, & Lamond, 2006). The task measures how fast subjects respond to a luminous-white-light presented on a black target stimulus. The display presents the visual stimulus, counting from zero to 60 seconds in 10 millisecond intervals. The PVT inter-stimulus interval varies randomly between 2,000 and 10,000 milliseconds, producing approximately 45 reaction times per five minute trial. The dependent variables (DVs) for the PVT were mean RT (ms) and the number of lapses (i.e., RTs > 500 ms).

6.2.3.2 Stroop task

The Stroop task, a measure of the executive function of response inhibition, has previously been used in research on dehydration (Szinnai, Schachinger, Arnaud, Linder, & Keller, 2005). The Stroop task consisted of two by two minute conditions, requiring participants to respond to the font colour via the corresponding colour on an alphanumeric keypad. For the matching word-pair condition the colour name was presented in the corresponding colour (e.g., 'GREEN' was presented in green font) for the non-matching word-pairs the colour name was presented in a non-corresponding colour (e.g., 'RED' was presented in blue font). Colour-word displays were made up of the words 'RED, BLUE, GREEN or YELLOW' presented on a standard 17" screen (resolution, 1280p x 800p). The DVs derived for the Stroop task were percentage correct and mean RT (ms) for both matching and non-matching word-pairs.

6.2.4 Activity data

Actiwatch-64 (Mini-Mitter Philips Respironics, Bend, OR) or Actical Z-series (Mini-Mitter Philips Respironics, Inc.) devices were worn on the non-dominant wrist, prior to and during the simulation, sampling movement at 32 Hz with an omnidirectional piezoelectric accelerometer. Accompanying software (Actical® version 3.0; Mini-Mitter Philips Respironics, Inc.) was used to analyse epoch-by-epoch time stamped physical activity counts for each participant. Physical activity was measured by summing the activity count for each 60 second epoch over the 55 minute physical work circuit before each cognitive test session (13:50 h, 15:50 h, 17:50 h), providing a total activity count measure for each circuit.

6.2.5 Hydration testing

Participants were provided *ad libitum* access to fluid, electrolytes and food, with portions developed in close consultation with Australasian Fire and Emergence Service Authorities Council representatives (Ferguson et al., 2011). Urine samples and total urine volumes were collected in the break opportunities provided at the end of each test session (i.e., 14:30 h; 16:30 h; and 18:30 h) after dinner, and during sleep. However since participants were not

always able to void urine at the requested times not all potential urine specific gravity (U_{sg}) samples (one for each three 2 h testing session per participant) could be obtained.

Hydration values were determined by performing a U_{sg} analysis using a portable refractometer (Atago, Japan). Prior to U_{sg} analysis researchers placed a drop of distilled water on the face of the prism, as standard, to adjust the instrument to 1.000 grams per milliliter ($g{\cdot}mL^{-1}$). Each of the U_{sg} samples and the corresponding cognitive performance values for the relevant test session were assigned a hydration status. U_{sg} values 1.000-1.019 $g{\cdot}mL^{-1}$ were classified as euhydrated, whilst values ≥ 1.020 $g{\cdot}mL^{-1}$ were classified as non-euhydrated (*approaching dehydration*). Samples were classified according to the published ranges with previous authors recommending a U_{sg} of < 1.020 $g{\cdot}mL^{-1}$ as a euhydrated state (Cheuvront, Kenefick, Sollanek, Ely, & Sawka, 2013) and a U_{sg} range of 1.022-1.034 $g{\cdot}mL^{-1}$ indicative of dehydration (Cheuvront et al., 2010). There has been some debate regarding dehydration assessment in recent studies, for their alternative views the reader is referred to Armstrong, Maughan, Senay, and Shirreffs (2013) and Cheuvront, Kenefick, and Charkoudian (2013).

6.2.6 Statistical analyses

The method of splitting the data and analyses were based on previous research methodologies (Dorrian, Hussey, & Dawson, 2007; Dorrian, Roach, Fletcher, & Dawson, 2006; Dorrian, Roach, Fletcher, & Dawson, 2007). However, this method resulted in groups of uneven size for both the *control* condition (euhydrated, n = 37; and non-euhydrated, n = 18) and for the *hot* condition (euhydrated, n = 25; non-euhydrated, n = 7). As there is potential to violate the assumption of homogeneity of variance, two checks were conducted to ensure robustness and therefore deflating the risk of a Type 1 error. First, the ratio of largest to smallest groups was less than 4:1, and secondly, the ratio of variances in each cell was less than 10:1 (Tabachnick & Fidell, 2007). Since these conditions were met, there was no need to randomly exclude cases in low and moderate groups to even out numbers, thus avoiding any unnecessary data loss. Importantly, however, this method of splitting the data also resulted in repeated measurements for individual firefighters within hydration statuses for both conditions. To account for this ‘participant ID’ was specified as a random effect in order to control for the inter-correlated observations within hydration statuses for firefighters in both conditions.

Since previous research has shown exercise can facilitate aspects of cognitive performance (Tomporowski, 2003) a preliminary mixed model analysis of variance was conducted to assess differences in physical activity (subsequently entered into the main analyses as a covariate) with 3 fixed factors of condition (2 levels – *control*, *hot*), hydration status (2 levels – euhydrated/ non-euhydrated) and trial/time-of-day (3 levels – 13:50 h, 15:50 h, 17:50 h) and a random factor of participants (*n* = 73). Results revealed a significant main effect of trial on physical activity $F_{2,86}=3.71$, $p=0.029$ and also an interaction effect of condition by hydration status $F_{1,137}= 4.17$, $p=0.043$. Hence physical activity was subsequently entered into the analyses as a covariate in models of cognitive performance but was not significant with the exception of Stroop percentage correct on matching word-pairs (Table 6.2). To assess the main and interaction effects of condition, hydration status, and trial/time-of-day on cognitive dependent variables, data were analysed using a mixed model analysis of variance with 3 fixed factors of condition (2 levels), hydration status (2 levels) and time-of-day (3 levels) and random factors of participants (*n* = 73) and physical activity as a covariate. Dependent variables consisted of PVT mean RT and lapses and Stroop RT and percentage correct for matching and non-matching word-pairs. All statistical analyses were conducted using SPSS 20.0. The denominator degree freedoms for *F* statistics were computed using the Satterthwaite approximation method. Uncorrected degrees of freedom are reported. LSD post-hoc contrasts were specified between levels of the fixed effect factors.

6.3 Results

6.3.1 PVT performance

Main and interaction effects on PVT mean RT and lapses are reported in Table 6.2. For the main effect of hydration status on mean RT non-euhydrated values were significantly higher compared to euhydrated values, when averaged over conditions and trials. For the interaction effect of hydration status by condition on PVT mean RT post-hocs showed non-euhydrated values in the *hot* condition were significantly higher compared to euhydrated values in both the *control* and *hot* conditions, when averaged over trials (Figure 6.1A).

For the main effect of time-of-day on lapses values were significantly higher by the 17:50 h trial compared to both the 13:50 h ($p<0.001$) and 15:50 h ($p=0.002$) trials, when averaged

over hydration status and conditions. For the interaction effect of hydration status by time-of-day on lapses, post-hocs showed by the 17:50 h trial non-euhydrated values were significantly higher than euhydrated values ($p<0.001$), when averaged over conditions. For the interaction effect of condition by time-of-day on lapses, post-hocs showed by the 17:50 h trial values in the *hot* condition were significantly higher than the *control* condition ($p=0.003$), when averaged over hydration status. For the three-way interaction effect on lapses (i.e., hydration status by condition by time-of-day) post-hocs showed by the 17:50 h trial, non-euhydrated values in the *hot* condition were significantly higher than euhydrated values ($p<0.001$), and also significantly higher than both euhydrated ($p<0.001$) and non-euhydrated values ($p=0.001$) in the *control* condition (Figure 6.1B). Additionally, for lapses by the 17:50 h trial non-euhydrated values in the *hot* condition were significantly higher than both the 13:50 h ($p<0.001$) and 15:50 h trials ($p<0.001$; Figure 6.1B).

6.3.2 Stroop simple and complex cognitive measures

Main and interaction effects on Stroop RT for both matching and non-matching word-pairs are reported in Table 6.2. For the main effect of condition on Stroop RT for matching word-pairs values in the *control* condition were significantly higher compared to the *hot* condition, when averaged over hydration status and trials. For the interaction effect of condition by time-of-day on Stroop RT for matching word-pairs, post-hocs showed values in the *control* condition for the 13:50 h ($p=0.024$) and 15:50 h ($p=0.019$) trials were significantly higher relative to the *hot* condition. When averaged over hydration status (Figure 6.2A).

For the main effect of condition on Stroop RT for non-matching word-pairs values in the *hot* condition were significantly higher compared to the *control* condition, when averaged over hydration status and trials. For the main effect of time-of-day on Stroop RT for non-matching word-pairs by the 17:50 h trial values were significantly higher compared to both the 13:50 h ($p=0.013$) and 15:50 h ($p=0.002$) trials, when averaged over hydration status and conditions. For the interaction effect of hydration status by time-of-day on Stroop RT for non-matching word-pairs post-hocs showed by the 17:50 h trial non-euhydrated values were significantly higher than euhydrated values ($p=0.003$), when averaged over conditions (Figure 6.2B). Additionally, for Stroop RT on non-matching word-pairs by the 17:50 h trial non-euhydrated values in *hot* condition were significantly higher than both the 13:50 h ($p=0.010$) and 15:50 h

trials ($p=0.001$; Figure 6.2B). There were no statistically significant main or interaction effects on Stroop percentage correct (Table 6.2) for both matching (Figure 6.2A) and non-matching word-pairs (Figure 6.2B).

Table 6.2 Results of mixed-effect ANOVAs with physical activity as a covariate, hydration status, condition and time-of-day as fixed effects and participant ID as a random effect on measures of cognitive performance.

	Physical activity			Hydration status			Condition			Time-of-day			Hydration status by condition			Hydration status by time-of-day			Condition by time-of-day			Hydration status by condition by time-of-day		
	F	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*
PVT RT	0.44	1,100	0.508	6.26	1,138	**0.014**	1.48	1,83	0.228	3.05	2,102	**0.052**	4.17	1,138	**0.043**	1.45	2,102	0.239	1.35	2,100	0.264	0.99	2,101	0.374
PVT Lapses	1.32	1,89	0.254	3.13	1,134	0.079	3.82	1,91	**0.054**	7.15	2,113	**0.001**	3.45	1,134	0.065	7.72	2,115	**0.001**	4.42	2,112	**0.014**	6.99	2,114	**0.001**
Stroop RT (M)	0.12	1,141	0.730	0.09	1,100	0.767	4.01	1,82	**0.049**	0.8	2,90	0.454	3.62	1,94	0.060	0.19	2,90	0.828	3.51	2,78	**0.035**			
Stroop % (M)	1.77	1,112	0.186	0.08	1,135	0.781	0.16	1,91	0.695	0.15	2,108	0.861	1.98	1,131	0.62	0.37	2,110	0.690	0.07	2,87	0.930			
Stroop RT (N)	0.71	1,139	0.403	3.47	1,94	0.065	6.84	1,79	**0.011**	4.95	2,86	**0.009**	0.06	1,89	0.810	5.19	2,86	**0.007**	0.90	2,76	0.412			
Stroop % (N)	6.50	1,93	**0.012**	0.65	1,141	0.423	0.33	1,89	0.570	1.35	2,114	0.264	0.00	1,141	0.949	0.53	2,118	0.588	1.19	2,91	0.309			

(M) Matching (N) Non-matching

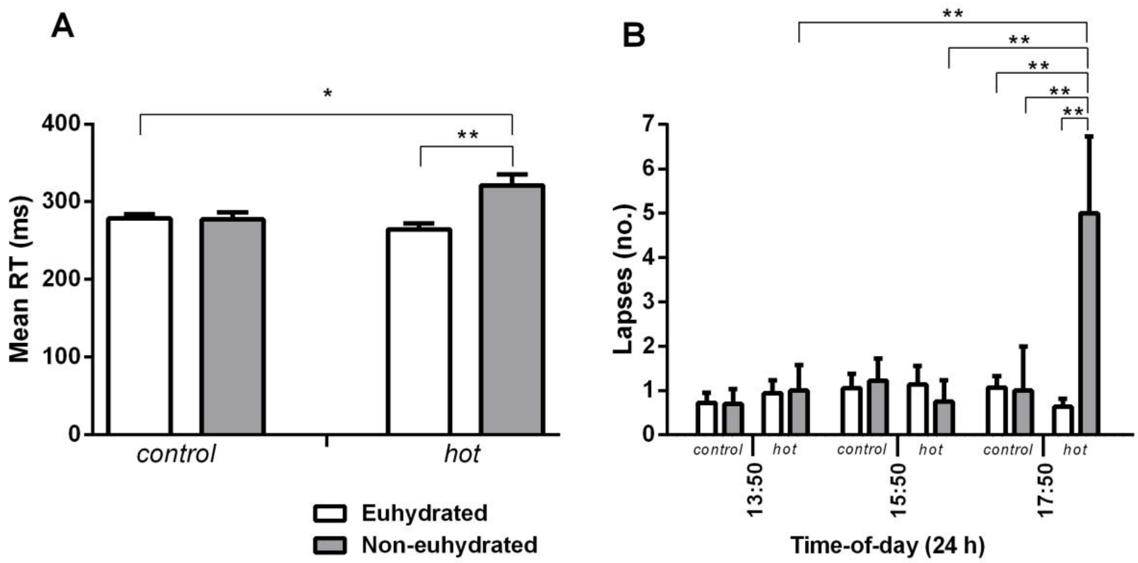

Figure 6.1 PVT. Panel A: PVT mean RT. Plotted as the interaction of condition by hydration status averaged over trials. Panel B: PVT lapses. Plotted as the interaction of condition by hydration status and time-of-day. Symbols denote significant LSD post-hoc differences: *p<0.05, **p<0.01. Values represent mean ± SEM.

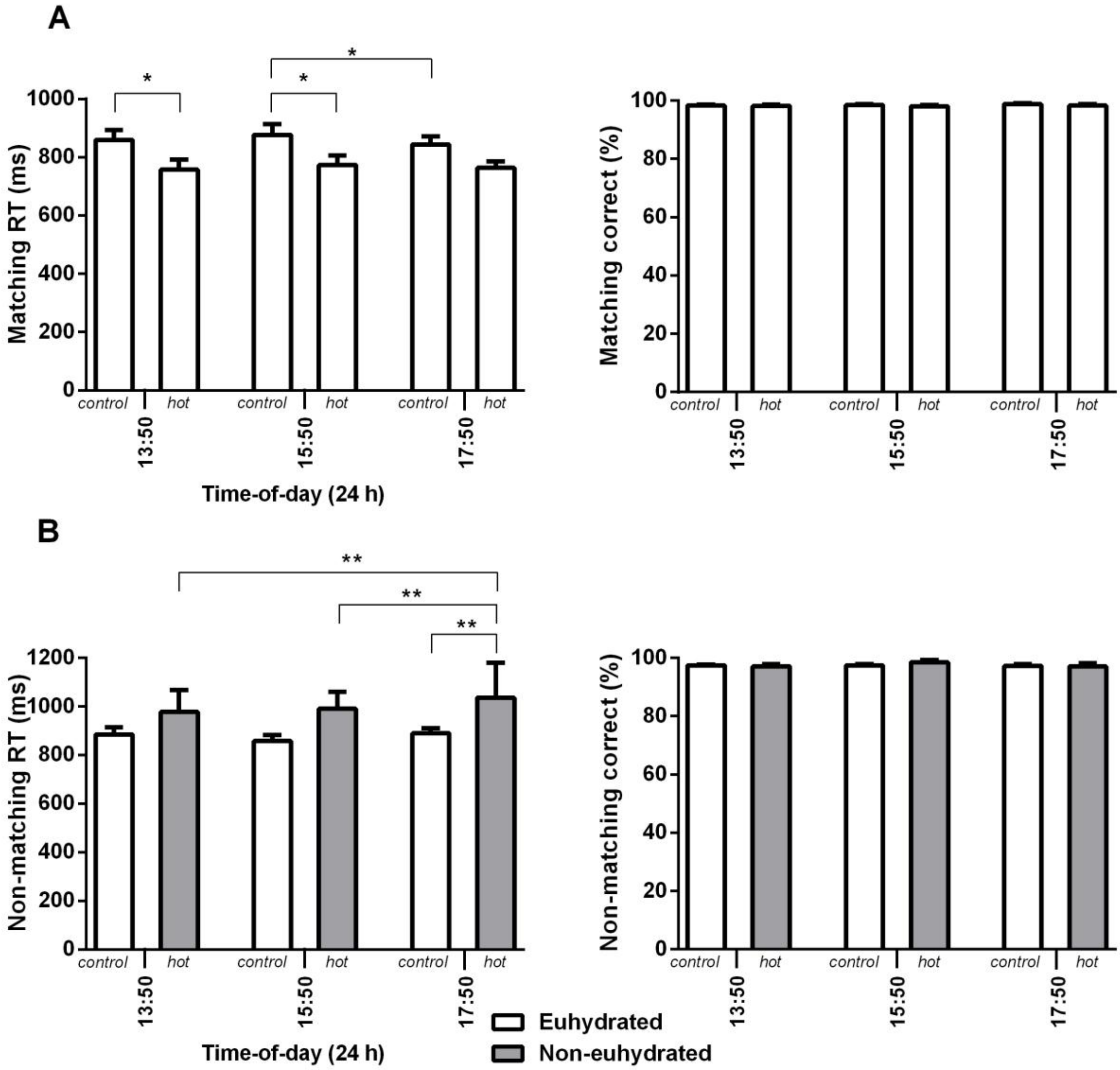

Figure 6.2 Stroop task. Panel A: Stroop matching word-pairs RT and percentage correct. Plotted as the interaction of condition by time-of-day, averaged over hydration status. Panel B: Stroop non-matching word-pairs RT and percentage correct. Plotted as the interaction of hydration status by time-of-day, averaged over conditions. Symbols denote significant LSD post-hoc differences: $*p<0.05$, $**p\leq0.01$. Values represent mean ± SEM.

6.4 Discussion

The aim of the present study was to examine the effect of hydration in either temperate or warm conditions on the cognitive performance of firefighters carrying out wildfire suppression tasks. Results demonstrated PVT performance remained relatively stable in thermoneutral temperature regardless of *approaching dehydration*, although in the heat

performance impairments on both PVT mean RT and lapses were observed. For the Stroop task results showed the percentage of correct responses was not significantly affected by temperature, hydration status or time-of-day (see Section 5.2.2). Results also showed for the Stroop task response times to matching word-pairs were impaired in temperate conditions compared to the heat, over the early- and mid-afternoon trials. However, on non-matching word-pairs, reaction time performance was most impaired when *approaching dehydration* by the late-afternoon, regardless of external temperature. For the results to provide contrast to other research where comparisons are made, it should be noted that non-euhydrated values correspond to a body weight loss of < 1%. While *approaching dehydration* values correspond to body weight losses in the range of 3-5% (Popowski et al., 2001).

For measures of the PVT, *approaching dehydration* was associated with different outcomes in the heat as compared to a thermoneutral temperature range. For example, PVT mean RT under normal temperatures remained stable regardless of *approaching dehydration*. However in the heat *approaching dehydration* resulted in significantly impaired performance relative to the *hot* hydrated, *control* hydrated and *approaching dehydration* groups. This is consistent with previous research showing dehydration losses of 1-2% B_m do not typically result in cognitive impairments in cold or thermoneutral (~20°C) temperatures (Adan, 2012; Leibowitz, Abernethy, Buskirk, Bar-or, & Hennessy, 1972; Neave et al., 2001; Serwah & Marino, 2006). However, in heated environmental conditions (39-45°C T_{db}) dehydration losses of ≥ 2% B_w induced from moderate exercise have resulted in cognitive declines on measures of psychomotor control (Sharma et al., 1986) and motor speed on a visuo-motor tracking task (Gopinathan et al., 1988). In contrast to the relatively stable performance of the PVT under thermoneutral temperatures with *approaching dehydration*, previous studies have reported dehydration impairs psychomotor performance regardless of the method of induction (Cian et al., 2001; Cian et al., 2000; Petri, Dropulic, & Kardum, 2006; Suhr, Hall, Patterson, & Niinistö, 2004). Results also showed that PVT Lapses increased in the heat with dehydration, although not with euhydration, in the late-afternoon, suggesting the effects of dehydration at this time impair performance on this measure beyond dehydration in cooler or more mild temperatures.

For Stroop RT on non-matching word-pairs, the cognitive measure relying on the executive function of response inhibition, findings showed a speed-accuracy trade-off. That is, percentage correct remained stable over the simulated workshift for both hydrated and *approaching dehydration* groups (i.e., a $U_{sg} \geq 1.020$ g·mL^{-1}), whilst RT became significantly slower in the *approaching dehydration* group by the late-afternoon regardless of ambient temperature. This finding is consistent with previous studies on dehydration demonstrating speed-accuracy trade-offs on complex self-paced cognitive tasks, albeit in the opposite direction, with faster response times at the expense of an increase in errors (Grego et al., 2005; Tomporowski et al., 2007). These findings are also generally consistent with research showing that regardless of the method of dehydration, deficits will result for measures of complex cognitive functions when dehydration levels exceed 2% B_m loss from passive heat or exercise alone (Cian et al., 2001; Cian et al., 2000; Ganio et al., 2011). Although in contrast to the present findings, no effects of dehydration on cognitive performance have been reported on a variety of complex tests, including the Stroop task (Szinnai et al., 2005), under numerous experimental conditions (Armstrong et al., 2012; Grego et al., 2005; Serwah & Marino, 2006; Tomporowski et al., 2007).

Findings also revealed physical activity was a significant co-variate for Stroop percentage correct for non-matching word-pairs, however performance remained relatively stable and was not affected by temperature, hydration status or time-of-day. It may be the diminishing effects of these factors is counterbalanced,masked, or even improved by the increase in arousal seen from exercise, hence resulting in the stable performance observed. For example, performance improvements in reaction time have been observed immediately following exercise durations greater than 20 minutes (Chmura et al., 1998; Collardeau, Brisswalter, & Audiffren, 2001; Collardeau, Brisswalter, Vercruyssen, et al., 2001).

The findings of this study have a number of practical implications. Firstly, firefighter's simple mental functions may deteriorate when *approaching dehydration* and when ambient temperatures exceed 32°C, and also if it is late in the afternoon. This decline in performance is most likely due to a number of factors including the time of day, since it is near the end of the workshift, and more specifically deteriorates due when physical activity, heat, and dehydration are combined. Presenting a significant risk as firefighters perform 12-16 h shifts during the day and night suppressing wildland fires known to reach temperatures in excess of 45°C (Teague et al., 2010). The findings also suggest that if firefighters need to maintain

vigilance and react quickly that dehydration and hot temperatures may increase the risk of impaired performance. For instance when firefighters have to avoid falling debris, evade rapidly degrading environments or avoid less favourable terrains. Hence, fire agencies should be aware that a temperature range of 33-35°C provides a guide as to when firefighters aged between 29 and 32 years of age, in hotter temperatures will begin to experience a deterioration of basic mental functions as dehydration ensues. Since the effects of age were not examined as potential moderators of cognitive performance in this study, future research may want to benefit from this limitation by researching age-related declines in cognitive performance for the volunteer wildland firefighting population in Australia.

Furthermore, firefighter's complex mental functioning may be impaired irrespective of external temperature if they are *approaching dehydration* and it is late in the day (i.e., approximately 18:00 h). This highlights a significant issue as previous research has identified that firefighters arrive on shift dehydrated (Cuddy et al., 2008; Raines et al., 2012, 2013; Ruby et al., 2003) and either sustain that level of dehydration (Ruby et al., 2003) or increase it by the end of their work shift (Cuddy et al., 2008; Hendrie et al., 1997). Approaching dehydration late in the shift may impede the ability to plan, co-ordinate and execute life-saving exit strategies based on incoming cues from the environment (e.g. recognising smoke patterns that indicate changing conditions) and central information being relayed about the changing fire conditions. Increasing fluid and food supplies at staging areas and reminding crews to load firefighting vehicles with ample food and drink supplies for the duration of their shift is an important strategy. Furthermore, increasing safety controls such as peer-monitoring, and reminders from superiors encouraging workers to pay attention to their fluid intake whilst deployed in hotter temperatures, as it becomes later in the afternoon would also be beneficial. Although this study has a number of important practical implications for fire agencies one limitation is that the effect on firefighters' cognitive performance from multiple days of dehydration in similar or more extreme ambient temperatures remains to be determined.

In conclusion, this study simulated a wildfire suppression shift, allowing natural in-field *ad libitum* hydrating provisions, in either temperate or hot conditions to evaluate the cognitive performance of firefighters. Urine specific gravity dehydration analyses showed the *control* condition with 37 participants euhydrated and 18 participants non-euhydrated, and for the *hot* condition 25 participants were euhydrated and seven participants non-euhydrated. The results

revealed that the greatest deteriorations in both simple and complex cognitive functions were associated with *approaching dehydration* late in the afternoon. Fire agencies should consider a number of safety controls to manage individual health and safety such as peer monitoring, increasing food and fluid supplies etc., in order to minimise the risk of dehydration. This would maximise the mental effectiveness of firefighters during fire suppression operations. Future research may want to overcome a limitation of this study by aiming to determine whether dehydration in extremely hot or cool ambient temperatures, or for more prolonged durations results in changes to cognitive performance. Further, assessing the temperature ranges at which cognitive performance may be susceptible to dehydration will better inform the implementation of workplace strategies and guidelines.

Chapter 7: The Cognitive Performance of Australian Volunteer Firefighters During a Simulated Wildland Tour: The Impact of Sleep Restriction and Temperature

Abstract

Firefighters in the field are exposed to combinations of exercise, hot temperatures and sleep loss, although the effects on cognitive performance of these stressors individually and in combination, have not yet been examined in wildland firefighters. The aim of this study was to determine the effects on firefighters' cognitive performance of a three-day wildland fireground tour simulation with either full sleep opportunities or sleep restriction in thermoneutral or hot temperatures in the presence of daytime physical activity. Fifty-nine volunteer firefighters (age: 37.1 ± 14.8 years, mean ± SD) were allocated to one of three conditions: *control* (n = 23), *awake* (n = 25), or *awake/hot* (n = 11). The protocol consisted of a baseline day with an 8 h sleep opportunity followed by two experimental days with 8 h sleep opportunities for *control* condition or 4 h sleep opportunities for the *awake* and *awake/hot* conditions. For the *control* and *awake* conditions temperatures were set to 18-20°C and for the *awake/hot* condition set to 33-35°C throughout the day and 23-25°C throughout the night. During the simulated dayshift participants completed testing sessions consisting of self-paced physical work activities based on wildfire suppression, followed by the PVT, Stroop, and Go Nogo tasks. Results for PVT mean reciprocal RT showed a decline in the *awake* and *awake/hot* conditions over sleep restriction days. Also, lapses increased in the *awake* condition by the first day of sleep restriction and then in all conditions by the third and final day of the experiment. For the Stroop task, RTs to non-matching colour-words improved in all conditions by the final experimental day with an increase in the percentage of errors in the *awake/hot* condition. For the Go/Nogo task, RTs on Go stimuli increased by the first sleep restriction day in the *awake* condition and then increased in all conditions by the final experimental day. Go percentage correct also declined from the second sleep restriction day relative to the first in the *awake* condition. For Stroop inhibitory control all conditions improved by the final experimental day. In contrast, Go/Nogo response inhibition showed significant impairment for the *awake/hot* condition from the second day of sleep restriction relative to the first. Overall, the findings revealed PVT impairments with both sleep restriction and sleep restriction in the heat, while measures of automatic responding on the Go/Nogo task showed a clear effect of sleep restriction only. For the non-executive cognitive measures of the Stroop task findings showed a speed-accuracy trade-off with sleep restriction in the heat. Similarly, the executive function of Go/Nogo response inhibition showed impairment with sleep restriction and heat.

7.1 Introduction

Wildfires expose firefighting personnel to multiple occupational and environmental stressors, including restricted opportunities for sleep between consecutive shifts, long work hours and hot environmental temperatures (Aisbett et al., 2012; Cater et al., 2007; Cheney, 1976; Cuddy et al., 2008). Studies on the effects of these stressors in combination in the laboratory and the field are sparse (Aisbett et al., 2012). The only studies on firefighters' cognitive performance have reported small to no effects on response times or accuracy in response to live firefighting drills (Smith, Manning, et al., 2001) and in different configurations of firefighting equipment (Smith & Petruzzello, 1998). Given the gap in literature on firefighting, it is useful to examine laboratory studies on the effects of sleep loss, heat, and/or physical activity, individually and in combination on cognitive performance.

It is widely established that sleep loss affects performance on lower-level cognitive processes, such as automatic responding on the Psychomotor Vigilance Test, shown by delays in RT and an increase in lapses. PVT performance impairments have consistently been shown from studies of seven nights or more of sleep restriction (Belenky et al., 2003; Dinges et al., 1997; Van Dongen, Maislin, et al., 2003). Lesser durations of only two nights of sleep restriction have also been shown to impair PVT performance (Drake et al., 2001; Swann et al., 2006). Even a single night of partial sleep deprivation by itself (Innes et al., 2013; Schwarz et al., 2013), or in combination with heat and physical activity (Tokizawa et al., 2015) can deteriorate PVT performance.

Although the effects of sleep restriction individually or combined with other stressors on PVT performance have been widely studied, there has been less research examining the effects of sleep restriction on higher-order cognitive tasks relying on executive functions, such as response inhibition. Response inhibition or inhibitory control is the function necessary to prevent or withhold the initiation of an automatic or pre-potent response, when that response is no longer necessary (Drummond et al., 2006). The Stroop and Go/Nogo tasks are two widely cited measures assessing inhibitory control, although results for these tasks from sleep restriction studies often present contrasting findings (Balkin et al., 2004; Stenuit & Kerkhofs, 2008), or null results (Rossa et al., 2014; Stenuit & Kerkhofs, 2008). For example, one study concluded that the Stroop task is really sensitive to the effects of sleep restriction to

4 h for three nights, in a sample of women only (Stenuit & Kerkhofs, 2008). In contrast, another large-scale study on the comparative utility of cognitive tests to sleep loss showed no significant effects on Stroop task performance following restriction to 3 h sleep for seven nights (Balkin et al., 2004). Similarly, research using the Go/Nogo task has shown that sleep restriction to 4 h for two nights had no effect on performance (Stenuit & Kerkhofs, 2008). Furthermore, another study measuring the executive function of response inhibition using an emotional Go/Nogo task, showed performance was not affected following a single night of 3 h sleep (Rossa et al., 2014).

However, the suggestion that sleep loss may affect performance on these tasks is supported by findings from studies of partial sleep deprivation (i.e., a single night) showing decrements in Stroop task performance (Jarraya et al., 2013) and also with time-of-day impairments in the morning relative to the afternoon (Jarraya et al., 2014). Similarly, Go/Nogo task performance impairments have been reported following one or two nights of complete sleep loss (Bougard et al., 2015; Drummond et al., 2006). Time-of-day effects following physical exercise on Go/Nogo performance have also been reported with improved performance in the afternoon relative to the morning (Petit et al., 2013). For both the Stroop and Go/Nogo tasks, heat and physical activity have also been studied with impairments in Stroop performance shown during industrial work in the heat (Mazloumi et al., 2014), although no effect on Go/Nogo performance from exercise in the heat (Ando et al., 2015).

One reason for the discrepancy between sleep restriction studies for the Go/Nogo task is the use of variants of the paradigm, measuring cognitive processes other than response inhibition. For example, an emotional Go/Nogo task measures not only the ability of participants to successfully inhibit responses but also the cognitive processes of emotional regulation and impulse control (Rossa et al., 2014). Similarly, where Stroop task performance has been reported to be affected by sleep restriction it is sometimes unclear which component is being assessed. For example, when reporting increased total reaction times on the Stroop task, this may also be inclusive of RTs for incorrect responses (Stenuit & Kerkhofs, 2008). Since performance on a task is dependent on a range of cognitive processes, it is important to assess the low-level processes such as automatic responding through to the higher-order executive functions such as response inhibition, whilst distinguishing between the executive and non-executive components of a task (Swann et al., 2006).

To the authors' knowledge, the effects of two or more nights of sleep restriction, heat and physical activity combined on the PVT, Stroop and Go/Nogo tasks, has not yet been studied. Furthermore, findings from sleep restriction studies have not provided consistent results for the Stroop and Go/Nogo tasks where other studies of partial sleep deprivation or a single night's sleep loss show a consistent impairment in reaction time for the PVT. Furthermore, there is a gap in research literature on cognitive performance for volunteer firefighters undertaking multi-day fire campaigns. Hence, the aim of this study was to determine whether performance on a range of cognitive tasks including the PVT, Stroop, and Go/Nogo, is affected by sleep restriction in combination with heat compared to sleep restriction alone, and if these conditions differ from full sleep opportunities. Using a controlled laboratory simulation of a three-day wildland fireground tour including firefighter physical activities, with day- and night-time temperature manipulations and sleep loss.

7.2 Methods

7.2.1 Participants

Participants were recruited from state fire agencies in Australia (Australian Capital Territory, New South Wales, South Australia, Victoria, and Tasmania). Firefighters were allocated to one of three conditions, *control, awake* (sleep restriction) or *awake/hot* (sleep restriction and heat; demographics reported in Table 7.1). Ethics approval was obtained from the CQUniversity (H12/01-016) and Deakin University Human Research Ethics Committees (2010-170).

Table 7.1 Demographics of firefighters in the *control*, *awake* and *awake/hot* conditions. Values are in mean ± SD.

	control	*awake*	*awake/hot*
n	23	25	11
Age (y)	35.2 ± 15.5	38.5 ± 13.2	37.5 ± 15.6
BMI (kg·m^{-2})	27.0 ± 4.6	29.2 ± 4.9	26.7 ± 4.6
Male: Female	21:2	20:5	10:1

7.2.2 Procedure

The three-day simulated wildland fireground deployment consisted of a baseline day (BL) with an 8 h sleep opportunity (TIB 22:30-06:30 h). This was followed by two experimental days (E1 and E2) with either 8 h TIB (22:00-06:00 h) for the *control* condition or 4 h TIB (02:00-06:00 h) for the *awake* and *awake/hot* conditions. Single-blind procedures were used prior to participants' arrival at 19:00 h on the baseline night where participants were instructed on cognitive tests completing numerous practice trials and also informed on their sleep condition allocation.

On the baseline night and also the following morning participants completed cognitive task familiarisation before the final baseline trial was taken at 10:40 h for all cognitive measures, preceding the simulated fireground shift at 12:30 h. The simulated dayshift was comprised of four intermittent two hourly physical-cognitive test sessions. Each 2 h testing session consisted of a 55 minute physical work circuit involving wildland firefighter suppression tasks (for a detailed methodology Vincent et al., 2015), 20-25 minutes of physiological testing (for a detailed methodology Larsen, Snow, & Aisbett, 2015), and 20-25 minutes of cognitive testing, followed by a 15-20 minute rest period. For the PVT and Stroop task the trials were conducted at the same overlapping times each day 11:20 h (morning trial), 13:50 h (early-afternoon trial), 15:50 h (mid-afternoon trial), and 17:50 h (late-afternoon trial). For the Go/Nogo task trials were also taken at the same overlapping times each day 09:20 h (morning trial) and 17:50 h (late-afternoon trial).

For the *control* and *awake* conditions temperature was set to 18-20°C throughout the protocol. For the *awake/hot* condition from 11:30 h on baseline, temperature was set to 33-35°C during the day (06:00-18:00 h), and 23-25°C during the night (06:00-18:00 h). Temperature was maintained with a wireless temperature and humidity logger (HOBO ZW_003, One Temp Pty Ltd, Australia), three data receivers (HOBO ZW_RCVR, One Temp Pty Ltd, Australia) and included software (HOBO Pro Software, One Temp Pty Ltd, Australia). During the simulated dayshift participants wore personal protective clothing (approximately weighing 5 kg; International Organisation for Standardisation, ISO 15384:2003) including Proban® fire retardant cotton fabric jacket and trousers (Protex®, Australia), suspenders, boots, gloves, helmet, and goggles.

7.2.3 Cognitive performance measures

7.2.3.1 Psychomotor Vigilance Task

The PVT is a widely accepted measure of sustained attention with a small learning curve of only one to three trials (Dorrian et al., 2005). A validated five minute version of the task (Roach, Dawson, & Lamond, 2006) was presented on the personal digital assistant Tungsten E PalmPilot (Palm Inc., Sunnyvale, California; Thorne et al., 2005). The PVT task measures how fast participants respond to a luminous-white-light presented on a black target stimulus by pressing the correct key with their dominant hand, displaying the response time in milliseconds for 500 ms. The screen presents the visual stimulus counting from zero to 60 sec in 10 ms intervals, with the inter-stimulus interval varying randomly between 2,000 and 10,000 ms, producing approximately 45 RTs per five minute trial. The dependent variables for the PVT were mean reciprocated RT (RRT; i.e., 1/RT*1000; Dorrian, Rogers, & Dinges, 2004) and also the number of lapses (i.e., RTs > 500 ms).

7.2.3.2 Stroop task

This task consisted of two by two minute trial types, matching and non-matching. On matching colour-word trials the font colour of the word matches the text. On non-matching colour-word trials the font colour of the stimuli does not match the text (e.g., the word "RED" presented in blue font). For non-matching trials, participants must inhibit the pre-potent response of naming the written word in order to correctly respond by naming the colour of the font. Participants were instructed to 'respond as quickly and as accurately as possible', by naming the font colour of stimuli displayed via the corresponding colour on an alphanumeric keypad. Colour-word displays were made up of the words 'RED, BLUE, GREEN or YELLOW' presented individually against a black background until a response was registered. The computerised task was presented on a standard laptop pc 17" screen (resolution, 1280p x 800p) and administered using E-prime software version 2.0. The non-executive DVs for the task were median RTs for correct responses to non-matching colour-words and also the percentage of errors. The executive function of inhibitory control was calculated as non-

matching minus matching word-pair median RTs for correct responses (Barger et al., 2014; Burke, Scheer, Ronda, Czeisler, & Wright, 2015).

7.2.3.3 Go/Nogo task

For this task six different versions were constructed each presenting two geometric shapes of two sizes, large and small, in a homogenous colour with three of the shapes consisting of “Go” stimuli and one a “Nogo” stimulus. In a semi-random order one of the four shapes was shown in the centre of the screen for a period of 200 ms, with a 1300 ms inter-stimulus interval. Participants are required to respond with a space bar button press on the keyboard to all “Go” shapes and to withhold responses to “Nogo” shapes. Speed and accuracy were emphasised in the instructions. Each test had an average duration of four minutes and 35 seconds, displaying 181 images, with 63% consisting of “Go” stimuli. The computerised task was presented on a standard laptop pc screen (17” screen, resolution, 1280x800p) and administered using E-prime software (version 2.0). The non-executive DVs measuring automatic responding for the Go/Nogo task were RTs for correct responses to “Go” stimuli and the percentage correct (Drummond et al., 2006). The executive function of response inhibition was measured with percentage of incorrectly withheld responses to “Nogo” stimuli (Drummond et al., 2006). The Go/Nogo task is reported to show moderate to high test-retest reliability (Weafer, Baggott, & de Wit, 2013).

7.2.4 Activity data

Actiwatch-64 (Mini-Mitter Philips Respironics, Bend, OR) or Actical Z-series (Mini-Mitter Philips Respironics, Inc.) devices were worn prior to and during the experiment, sampling movement at 32 hertz. Physical activity was measured by summing all physical activity counts generated in each 60 sec epoch during the 55 minute physical work circuit before each cognitive test session.

7.2.5 Data analyses

To assess the main and interaction effects of condition, experimental day, and trial/time-of-day on cognitive dependent variables, data were analysed using a mixed model analysis of

variance with 3 fixed factors of condition (3 levels– *control*, *awake*, *awake/hot*), experimental day (3 levels – BL, E1, E2) and time-of-day (4 levels for the PVT and Stroop task – 10:40 h/11:20 h, 13:50 h, 15:50 h, 17:50 h; 2 levels for the Go/Nogo task – 10:40 h /09:20 h, 17:50 h) with a random factor of participants (n = 59) and physical activity as a co-variate. All statistical analyses were conducted using SPSS 20.0. The denominator degree freedoms for F statistics were computed using the Satterthwaite approximation method. LSD post-hoc contrasts were specified between levels of the fixed effect factors. Uncorrected degrees of freedom are reported.

7.3 Results

7.3.1 PVT mean RRT and lapses

There was a significant main effect of experimental day, but not condition, on PVT mean reciprocal reaction time (RRT) and lapses, and also a significant interaction effect of condition by experimental day on mean RRT (Table 7.2). For the main effect of experimental day on mean RRT by E2 values had significantly decreased relative to both BL ($p<0.001$) and E1 ($p<0.001$), when averaged over conditions and trials. For the interaction effect of condition by experimental day on mean RRT, post-hocs showed values significantly declined over E1 and E2 compared to BL in both the *awake* and *awake/hot* conditions, when averaged over trials (Figure 7.1A). Additionally, mean RRT by E2 had significantly declined from E1 in the *awake* and *awake/hot* conditions (Figure 7.1A).

For the main effect of experimental day on lapses by E2 values had significantly increased relative to both BL ($p<0.001$) and E1 ($p=0.001$), when averaged over conditions and trials. Post-hoc contrasts for condition by experimental day on lapses showed by E1 values had significantly increased compared to BL in the *awake* condition and by E2 values had significantly increased relative to BL in all conditions, when averaged over trials (Figure 7.1B). Additionally, lapses by E2 had significantly increased from E1 in the *awake* and *awake/hot* conditions (Figure 7.1B).

7.3.2 Stroop non-matching colour-words median RTs and percentage of errors

Results demonstrated a main effect of experimental day on both non-matching median RTs for correct responses and the percentage of errors (Table 7.2). Results also showed an interaction effect of condition by experimental day on non-matching median RTs and an interaction effect of trial by experimental day on non-matching percentage of errors (Table 7.2). There was also a main effect of stimulus type (i.e., the 'Stroop effect'; $F_{1,1725}$=564.029, p<0.001) with median RTs fastest for matching colour-words (mean = 705.201 ms, SD = 107.370 ms; results not reported) and slowest for non-matching colour-words (mean = 856.635 ms, SD = 153.624 ms).

For the main effect of experimental day on non-matching median RTs by E2 values had significantly decreased (i.e., improved) relative to BL (p<0.001) and E1 (p<0.001), when averaged over conditions and trials. For the interaction effect of condition by experimental day on non-matching median RTs, post-hocs showed by E2 values had significantly decreased relative to BL and E1, in all conditions, when averaged over trials (Figure 7.2A). Additionally, RTs by E1 had significantly decreased from BL in the *control* and *awake/hot* conditions, when averaged over trials (Figure 7.2A).

For the main effect of experimental day on non-matching errors percentage, by E2 values had significantly increased relative to both BL (p=0.044) and E1 (p=0.002), when averaged over conditions and trials. Post-hoc contrasts for condition by experimental day on non-matching errors percentage, revealed values had increased significantly by E2 relative to BL in the *awake/hot* condition, when averaged over trials (Figure 7.2B). Additionally, errors had significantly increased by E2 relative to E1 in the *control* condition and had also increased with marginal statistical significance by E2 compared to BL (p=0.056) in the *control* condition, when averaged over trials (Figure 7.2B).

For the interaction effect of time-of-day by experimental day on non-matching errors percentage, post-hocs showed on BL the 10:40 h trial was higher in errors compared to the 15:50 h trial (p=0.037), when averaged over conditions. For E1 the 13:50 h trial was lower in errors relative to both the 15:50 h (p=0.052) and 17:50 h trials (p=0.024). By E2 the 13:50 h

trial was higher in errors than the 15:50 h trial (p=0.024), and the 11:20 h trial was higher in errors than both the 15:50 h (p=0.010) and 17:50 h trials (p=0.027).

7.3.3 Go/Nogo task - Go RTs and percentage correct

Results demonstrated a main effect of experimental day and also an interaction effect of time-of-day by experimental day on Go RTs for correct responses (Table 7.2). For the main effect of experimental day on Go RTs by E2 values had significantly increased relative to both BL (p<0.001) and E1 (p<0.001), when averaged over conditions and trials. For the interaction effect of time-of-day by experimental day on Go RTs, by E2 the 09:20 h trial values had significantly increased compared to the 17:50 h trial (p=0.013), when averaged over conditions. Post-hoc contrasts on condition by experimental day for Go RTs also revealed by E1 values were significantly higher than BL in the *awake* condition and by E2 values were significantly higher in all conditions compared to BL, when averaged over trials (Figure 7.3A). Additionally, Go RTs by E2 were significantly higher than E1 in all conditions, when averaged over trials (Figure 7.3A).

For Go percentage correct post-hoc contrasts for condition by experimental day showed by E2 values were significantly lower than E1 in the *awake* condition, when averaged over trials (Figure 7.3B). Post-hoc contrasts for time-of-day by condition on Go percentage correct, showed the 17:50 h trial values were significantly higher compared to the 10:40 h/09:20 h morning trials (p=0.011) in the *awake* condition, when averaged over experimental days. Additionally, planned contrasts for time-of-day by experimental day on Go percentage correct showed by E2 the 17:50 h trial values were significantly higher compared to the 09:20 h trial (p=0.010), when averaged over conditions.

7.3.4 Executive functions: Stroop inhibitory control and Go/Nogo response inhibition

Results demonstrated a main effect of trial on Stroop inhibitory control and a main effect of experimental day on both Stroop inhibitory control and Go/Nogo response inhibition (Table 7.2). For the main effect of experimental day on Stroop inhibitory control by E2 values were significantly lower relative to BL (p<0.001) and E1 (p=0.002), when averaged over trials and

conditions. For the main effect of time-of-day on inhibitory control both the 13:50 h and 15:50 h trial values were significantly higher compared to the 17:50 h trial (p=0.002 and p=0.041, respectively), when averaged over experimental days and conditions. Post-hoc contrasts for condition by experimental day on inhibitory control showed by E2 values had significantly decreased (i.e., improved) in all conditions relative to BL, when averaged over trials (Figure 7.4A). Additionally, by E2 values had significantly decreased from E1 in the *control* and *awake/hot* conditions and had also declined from BL to E1 in the *control* condition, when averaged over trials (Figure 7.4A).

For the main effect of experimental day on Go/Nogo response inhibition by E2 values were significantly higher (i.e., impaired) relative to E1 (p<0.001), when averaged over conditions and trials. Post-hoc contrasts for condition by experimental day on response inhibition showed by E2 values were significantly higher compared to E1 (p=0.004) for the *awake/hot* condition, when averaged over trials (Figure 7.4B).

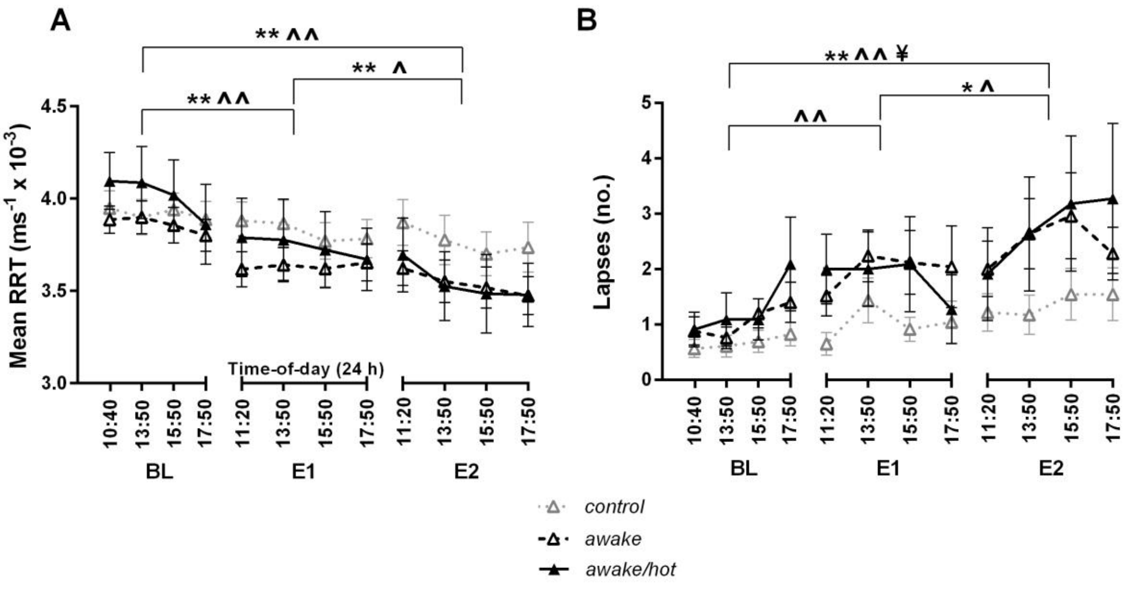

Figure 7.1 PVT. Panel A: Mean RRT. Panel B: Lapses. Plotted over baseline (BL) and experimental days one and two (E1, E2) by time-of-day with condition. Symbols denote a significant difference for conditions between experimental days: *(p<0.05), **(p<0.01) *awake/hot* condition; ^(p<0.05), ^^(p<0.01) *awake* condition; ¥(p<0.05) *control* condition. Values represent mean ± SEM.

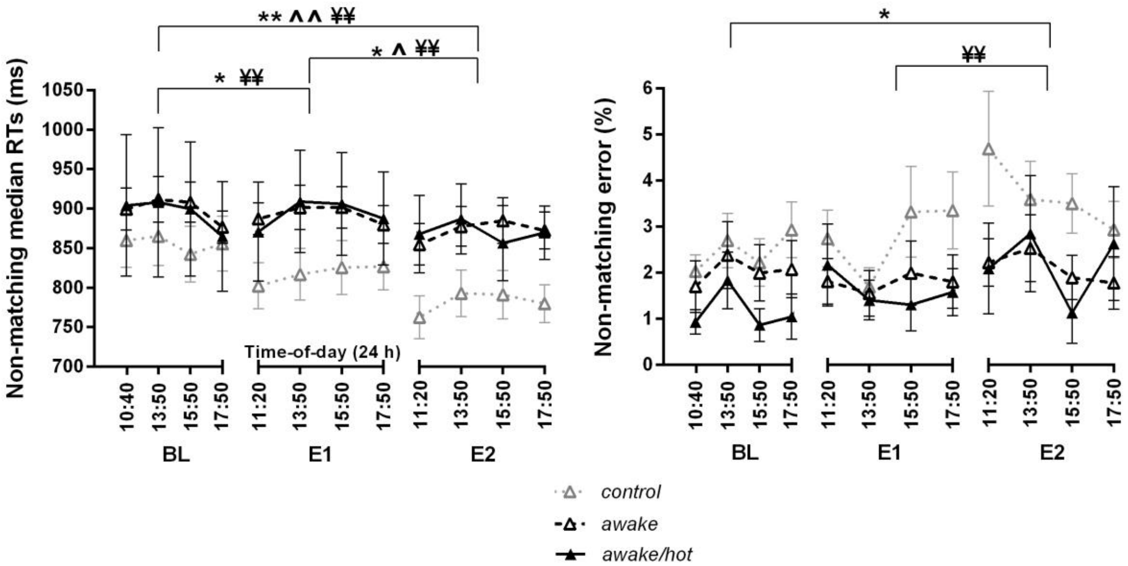

Figure 7.2 Stroop task. Panel A: Median RTs for correct responses to non-matching colour-words. Panel B: Percentage of errors on non-matching colour-words. Plotted as experimental day (BL, E1, and E2) by time-of-day with condition. Symbols denote a significant difference for conditions between experimental days: *(p<0.05), **(p<0.01) *awake/hot* condition; ^(p<0.05), ^^(p<0.01) *awake* condition; ¥¥ (p<0.01) *control* condition. Values represent mean ± SEM.

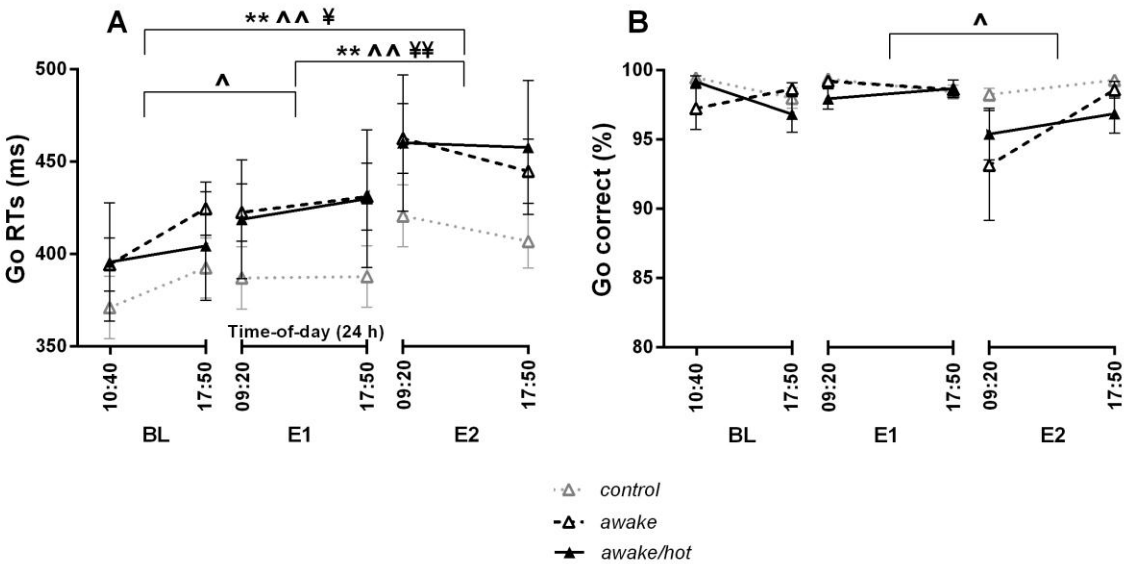

Figure 7.3 Go/Nogo task. Panel A: RTs on correct responses to Go stimuli. Panel B: Percentage of correct responses to Go stimuli. Plotted as experimental day (BL, E1, and E2) by time-of-day with condition. Symbols denote a significant difference for conditions

between experimental days: **(p<0.01) *awake/hot* condition; ^(p<0.05), ^^(p<0.01) *awake* condition; ¥ (p<0.05), ¥¥ (p<0.01) *control* condition. Values represent mean ± SEM.

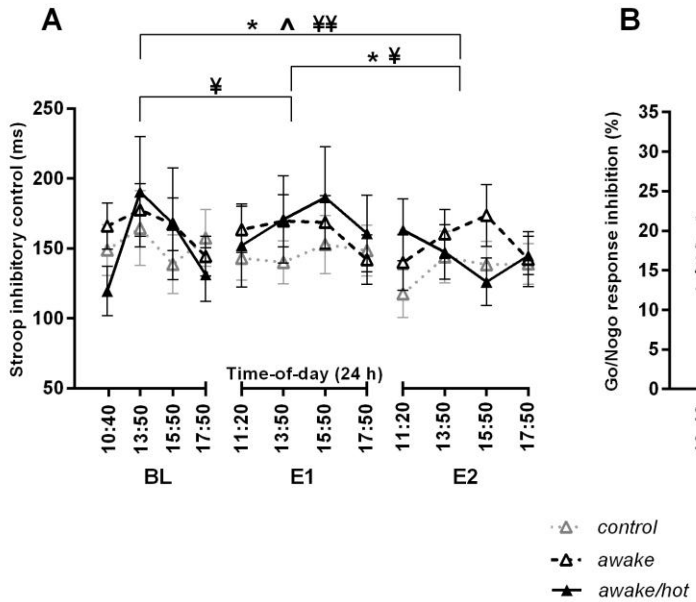

Figure 7.4 Executive function. Panel A: Stroop inhibitory control scores represent the difference between median RTs for correct responses to non-matching and matching colour-words. Panel B: Go/Nogo response inhibition scores represent the percentage of incorrect responses to Nogo stimuli. Plotted as experimental day (BL, E1, and E2) by time-of-day with condition. Symbols denote a significant difference for conditions between experimental days: * (p<0.05) *awake/hot* condition; ^(p<0.05) *awake* condition; ¥ (p<0.05), ¥¥ (p<0.01) *control* condition. Values represent mean ± SEM.

Table 7.2 Results of mixed-effect ANOVAs on PVT, Stroop and Go/Nogo tasks with fixed effects of condition, experimental day and time-of-day with participant ID as a random effect and physical activity as a covariate.

	Physical activity			Condition			Experimental day			Time-of-day			Condition by experimental day			Condition by time-of-day			Experimental day by time-of-day		
	F	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*
PVT RRT	1.88	1,678	.171	1.00	2,56	.375	32.52	2,651	**<.001**	2.54	3,642	.056	6.99	4,628	**<.001**	.52	6,625	.797	1.17	6,636	.322
PVT Lapses	.01	1,354	.929	2.50	2,56	.091	14.98	2,677	**<.001**	1.34	3,653	.260	1.42	4,633	.227	.21	6,623	.872	.937	6,646	.468
Stroop RTs	2.41	1,654	.121	.156	2,55	.156	30.81	2,623	**<.001**	2.76	3,618	**.042**	5.53	4,611	**<.001**	.620	6,609	.715	1.31	6,615	.249
Stroop error	5.27	1,622	**.022**	1.23	2,56	.300	5.08	2,644	**.007**	1.89	3,632	.129	2.06	4,614	.085	1.36	6,609	.228	2.70	6,624	**.014**
Stroop IC	6.64	1,650	**.010**	.614	2,56	.545	9.48	2,637	**<.001**	3.36	3,627	**.018**	1.02	4,612	.395	1.37	6,607	.225	1.62	6,620	.138
Go RTs	.03	1,310	.862	1.35	2,56	.267	29.54	2,291	**<.001**	1.02	1,298	.313	1.43	4,281	.225	.63	2,280	.535	6.34	2,291	**.002**
Go correct	2.68	1,104	.104	2.31	2,57	.108	2.30	2,335	.102	2.43	1,330	.120	.94	4,285	.444	1.42	2,284	.244	2.57	2,337	.078
Go/Nogo RI	.51	1,337	.477	.836	2,57	.439	7.63	2,308	**.001**	3.67	1,326	.056	.89	4,282	.473	.118	2,281	.889	2.21	2,309	.112

Stroop RTs - median RTs for correct responses to non-matching colour-words; Stroop error - percentage of incorrect responses to non-matching colour-words; Stroop IC - inhibitory control; Go RTs and Go correct - RTs and percentage of correct responses to Go stimuli on the Go/Nogo task; Go/Nogo RI - response inhibition.

7.4 Discussion

For PVT performance results showed mean RRT declined over sleep restriction days in both restriction conditions. Lapses increased on the first sleep restriction day in the sleep restriction condition only but differences were seen in all conditions by the final day of the experiment. For the Stroop task RTs for non-matching colour-words by the final experimental day were faster in all conditions. However, there was also an increase in the percentage of errors (i.e., a speed-accuracy trade-off) for non-matching colour-words in the sleep restriction and heat condition. Time-of-day effects on percentage of errors for non-matching colour-words were evident on baseline and experimental day two in the morning trials, with an increased percentage of errors relative to the mid- and late-afternoon trials, in the overall performance of all conditions. For the Go/Nogo task RTs on correct Go responses slowed on the first day of sleep restriction in the sleep restriction condition only and then by the final experimental day Go RTs were slower in all conditions. Performance on Go percentage correct also declined by the second day of sleep restriction relative to the first in the sleep restriction condition only. Time-of-day effects were also revealed for Go percentage correct with improved performance in the late-afternoon trial relative to the morning trial, in the sleep restriction condition only, when averaged over days. Although on sleep restriction day two, a similar pattern of time-of-day effects emerged irrespective of condition. For Stroop inhibitory control all conditions improved by the final day of the experiment while Go/Nogo response inhibition showed significant impairment for the sleep restriction and heat condition by the second day of sleep restriction relative to the first.

The findings of impairments on PVT automatic-response measures mean RRT and lapses on the first day of sleep restriction for the sleep restriction condition only, is consistent with two recent studies showing partial sleep deprivation to 4 h resulted in impairments on PVT mean RT and lapses (Innes et al., 2013; Schwarz et al., 2013). It should also be noted that cognitive performance under sleep restriction also varies between individuals and also within the individual themselves, due to intra-and inter-individual variability (Van Dongen, Maislin, et al., 2003). Although the exact day PVT performance impairments arise tends to vary between studies of sleep restriction for two consecutive nights. For example, two studies showed performance declines following the second night of sleep restriction to either 4 h or 4.8 h, although not first, on PVT median RT, mean RT, and lapses (Drake et al., 2001; Swann et al.,

2006). In contrast another study reported no effects following two nights of sleep restriction to either 3 h or 5 h on PVT median RT and lapses (Rupp et al., 2004).

The finding that PVT mean RRT declined following the first night of sleep restriction in the heat is also consistent with previous research on partial sleep deprivation to 4 h following exercise in 35°C heat (Tokizawa et al., 2015). This study also reported that the number of lapses increased following only a single night of sleep deprivation in the heat (Tokizawa et al., 2015). Although in this present analyses, lapses did not increase in the heat until following the second night of sleep restriction. However, the effect of heat by itself is unclear with other research showing no effect on PVT performance from heat with exercise (Parker et al., 2013), and also immediately following exercise in thermal firefighting personal protective clothing (Morley et al., 2012).

For the non-executive components of the Stroop task, results showed a speed-accuracy trade-off for non-matching colour-words in the sleep restriction and heat condition, by the second night of sleep restriction, with faster reaction times but lower accuracy. This finding is consistent with a previous study showing partial sleep deprivation to 2 h resulted in a speed-accuracy trade-off, with improved response times although an increased percentage of errors, on a Stroop task containing non-matching colour-word trials (Tassi et al., 2006). Although the separate effects of sleep restriction to 4 h for three nights (Stenuit & Kerkhofs, 2008), or industrial work in 33°C heat (Mazloumi et al., 2014), have individually been associated with impairments in both RTs and errors on non-matching colour-words. Thus for the present data, the increase in the percentage of errors may result from individuals adopting the strategy of increasing their RT performance at the expense of decreasing accuracy, when under combined conditions of sleep restriction and heat. Regardless of being instructed to simply, ‘respond as quickly and accurately as possible’. Hence, it may be both the effects of heat, and sleep restriction, that results in a speed-accuracy trade-off on performance for the Stroop task, which would be plausible given impairments shown from either sleep restriction or heat alone in previous research (Mazloumi et al., 2014; Stenuit & Kerkhofs, 2008; Tassi et al., 2006).

Results for the sleep restriction condition showed no change in errors and an improvement in RTs for non-matching colour-words, suggesting that sleep restriction alone had a minor effect on non-executive measures of Stroop performance. This finding is consistent with previous sleep restriction research comparing the sensitivity of cognitive tests for seven nights of sleep

restriction to either 3 h, 5 h, 7 h or 9 h TIB (Balkin et al., 2004). Which found no significant effects on Stroop RTs and the percentage correct for non-matching colour-words (Balkin et al., 2004). Importantly, practice effects have also been reported during sleep loss protocols with results showing faster RTs to non-matching colour-words, whilst the percentage of errors is unaffected (Sagaspe et al., 2006). For the present findings, similar results were shown for the sleep restriction condition and also in some instances the *control* condition and this may reflect learning or practice effects.

Finally, for non-executive measures of the Stroop task results also showed time-of-day effects, with an increased percentage of errors for non-matching colour-words in the morning trials relative to the mid- and late-afternoon trials, on baseline and experimental day two, regardless of condition. These variations in performance on the Stroop task at different times of the day compared to the PVT may reflect the different underlying processes measured, that is executive function and vigilance, respectively. These results are consistent with partial sleep deprivation research showing for both 8 h and 4 h sleep conditions, that accuracy decreased on the Stroop task in the afternoon and evening sessions relative to the morning trial (Jarraya et al., 2014).

For the measures of automatic responding on the Go/Nogo task findings showed Go RTs slowed after the first night of sleep restriction and Go percentage correct declined between sleep restriction nights, in the sleep restriction condition only. This result is consistent with previous research showing Go/Nogo RTs slowed following two consecutive nights of sleep restriction to 4 h (Stenuit & Kerkhofs, 2008). Impairments in the proportion of correct Go responses and Go RTs were also found following 55.75 h and 31.75 h of complete sleep loss (Drummond et al., 2006). The present results also showed Go RTs slowed in the sleep restriction and heat and *control* conditions by the final day of the experiment and also between experimental/sleep restriction days. The only other research examining the effects of heat and exercise, although without sleep restriction, on the Go/Nogo task did not report any significant difference for Go RTs following 10 minutes of cycling, compared to rest in 35°C air temperature (Ando et al., 2015). For the present results there appears to be a clear effect of sleep restriction on the measures of automatic responding Go RTs and Go percentage correct. Although, the impairment for Go RT performance observed in all conditions over the duration of the experiment, is similar to the pattern of deterioration shown for the PVT measure of automatic responding lapses. One explanation for these findings, is that

performance on these lower-level cognitive processes may have been influenced by the effect of repeated testing sessions with a moderate to high mental (Wright, Valdimarsdottir, Erblich, & Bovbjerg, 2007) and physical workload (Vincent et al., 2015).

For the Go/Nogo task time-of-day effects were also found for Go RTs and percentage correct, revealing the late-afternoon trial displayed improved performance compared to the morning trial regardless of condition by the final experimental day. This result is consistent with a previous study on time-of-day effects and exercise sessions showing Go RT performance was significantly better in the afternoon compared to the morning testing sessions (Petit et al., 2013). Results also showed poorer performance on Go percentage correct for the sleep restriction condition in the morning trial compared to the late-afternoon trial over experimental days. Similarly, Go RTs have been shown to slow in the morning test following a night of complete sleep deprivation as compared to a nights' normal rest (Bougard et al., 2015).

Findings for the executive function of Stroop inhibitory control showed all conditions were faster by the final day of the experiment, indicating the sleep loss conditions had little effect on inhibitory control. This finding is also consistent with applied research showing Stroop inhibitory control performance did not vary in workers obtaining 6 h to 7 h sleep for two consecutive workdays (Barger et al., 2014). Similarly, no change in inhibitory control was reported during the extended 24 h workshift for workers obtaining 1.88 h of sleep in naps, although there was a significant detriment for workers obtaining 3.4 h sleep. However, this impairment in Stroop inhibitory control was noted to reflect sleep loss in addition to a circadian misalignment in performance (Barger et al., 2014). Another study using the forced desynchrony protocol also showed inhibitory control did not vary with increasing time awake, although a strong circadian variation was evident showing performance was most impaired at a time corresponding to 1 h to 2 h after habitual awakening (Burke et al., 2015). Similarly, for the present results inhibitory control displayed variations in performance throughout the work day with slower RTs in the early- and mid-afternoon trials compared to the late-afternoon, regardless of condition or experimental day. These findings suggest a relatively minor effect of sleep loss on Stroop inhibitory control, although may provide support for the circadian modulation of performance (Barger et al., 2014; Burke et al., 2015).

In contrast to the improvements shown for Stroop inhibitory control, the executive function of Go/Nogo response inhibition showed impaired performance in the sleep restriction and heat condition, with increased errors by the second day of sleep restriction compared to the first. Go/Nogo task performance impairments on response inhibition have also been reported with extreme sleep loss periods of either 23 h (Drummond et al., 2006), or 24 h (Chuah et al., 2006). Nonetheless, the present findings showed the sleep restriction condition did not display any impairment for Go/Nogo response inhibition, suggesting the addition of heat may have been responsible for deteriorations observed when these conditions were combined. This would be consistent with other research showing no impairments on response inhibition to fearful faces on an emotional Go/Nogo task after sleep restriction to 3 h for one night (Rossa et al., 2014). Similarly, Go/Nogo response inhibition has been shown not to vary during three consecutive nights of exposure to noise induced sleep disturbances (Schapkin et al., 2006a, 2006b) and also between self-rated good and poor sleepers (Breimhorst et al., 2008).

A limitation of the current study is that repetitious use of the Stroop task can result in a practice effect that may lead participants to develop a reading suppression response and could potentially mask the effects of sleep restriction (Dulaney, Rogers, & Rayner, 1994; Sagaspe et al., 2006). However, had participants adopted this strategy it would be expected that non-matching and matching trial RTs would not differ significantly (Cain, 2011). However, results showed RTs were longer for non-matching compared to matching trials, consistent with the standard Stroop effects (MacLeod, 1991), and indicate that performance on the task continued to require inhibitory control.

In conclusion for lower-level cognitive PVT measures, findings showed declines in both sleep restriction conditions over sleep restriction days. For the measures of automatic responding on the Go/Nogo task there was a clear effect of sleep restriction showing in impairments on Go RTs and Go percentage correct. For the executive function of Stroop inhibitory control, performance improved in all conditions over the experiment. In contrast, for the executive function of Go/Nogo response inhibition, findings revealed impaired performance between days of sleep restriction for the sleep restriction and heat condition, Suggesting the addition of heat to sleep restriction may have been responsible for the deteriorations observed in Go/Nogo response inhibition. In real-world firefighting settings these results highlight a risk where firefighters may be either sleep deprived or sleep deprived

in the heat and require fast response times to evade hazards on the fireground. For example, a lapse in attention might be the difference in dodging falling debris, such as a tree or a burning environment. Higher-order cognitive capacity such as maintaining situational awareness is also critical for health and safety on the fireground and can be compromised. An example of this is being vigilant to secondary environmental cues while performing the primary task (Haslam, 1984). As the effects of heat are often inseparable from dehydration this has also been identified as another major stressor of wildland fighting (Ruby et al., 2003). Future research may want to consider the effects of sleep restriction, temperature and hydration on cognitive performance, either in firefighters or in the laboratory.

Chapter 8: General Discussion

8.1 Background

This thesis contributes to the body of scientific literature examining the interactions between sleep duration, sleep architecture, ambient temperature, physical activity, hydration and cognitive performance, as well as examining more specifically the effects of sleep restriction. More practically, it looked at these interactions, particularly of sleep restriction and temperature, in a population of volunteer rural firefighters and this has never been examined before. The studies employed in this thesis were designed to inform the literature by providing tightly controlled laboratory experimental designs simulating with high reliability and validity the types of occupational tasks and environmental stressors of wildland firefighting experienced during single- and multi-day wildfire suppression operations. The methodology utilised a previously validated wildfire simulation with relevant physical work tasks and cognitive performance measures in all studies (1, 2, 3, and 4 – Chapters 4, 5, 6, and 7) to quantify the effects of occupational and environmental stressors on firefighters. Although controlled conditions were used, examining cognitive performance and sleep architecture for firefighters in the wildfire environment is particularly difficult to institute between work tasks and duties in field settings. There are some limitations with a controlled study including an absence of fluctuating variables such as wind speed, radiant heat, and smoke exposure that are present in wildfire environments and are likely to impact the relationship between temperature, physical activity, hydration, sleep architecture and cognitive performance.

The purpose of each experimental chapter in this thesis was to inform the following research aims:

1. The aim of the first study (Chapter 4) was to determine whether changes in sleep architecture in the heat are significantly different from normative temperatures during simulated wildland firefighter suppression.

2. The aim of the second study (Chapter 5) was to quantify whether changes in sleep architecture from sleep restriction in the heat, are significantly different from those of sleep restriction in temperate conditions and if these conditions differ from full sleep opportunities during simulated wildland firefighter suppression.

3. The aim of the third study (Chapter 6) was to assess whether changes in cognitive performance and hydration from physical activity in heat are different from thermoneutral temperatures during a single simulated wildfire suppression shift.

4. The aim of the fourth study (Chapter 7) was to examine if the effects on cognitive performance of sleep restriction, and heat, whilst accounting for physical activity, are different from sleep restriction and physical activity in thermoneutral temperatures, and if these conditions differ from full sleep opportunities during simulated wildland firefighter suppression.

8.2 Summary of research findings and contributions to the literature

The effects of hot dayshifts and night-time temperatures on sleep architecture had not previously been examined in volunteer rural firefighters. The only research available during multi-day wildfire suppression deployments had been limited to subjective self-report measures (Cater et al., 2007; Gaskill & Ruby, 2004) and more recently actigraphy data (Vincent et al., 2016). However no objective measurements of sleep stages, whether working and sleeping in temperate (i.e., *control*) or *hot* conditions had been quantified at all for firefighters under any conditions either during deployments or under laboratory simulated conditions. Thus, Study 1 provided the first objective data of sleep for Australian volunteer firefighters during a simulated three-day four-night wildland fireground deployment in either cool to neutral, or hot temperatures. The results of the first study revealed that both working and sleeping in the heat, in day and night-time temperatures of 33-35°C and 23-25°C, respectively, produced similar effects on sleep architecture as working and sleeping in temperate day and night-time temperatures of 18-20°C.

Hot ambient temperatures were not associated with any differences in sleep architecture compared to the thermoneutral temperatures, with exception of N1 or Stage 1 sleep. Under thermoneutral temperatures N1 sleep remained constant over the four nights of the simulated deployment. While in the heat, N1 sleep significantly declined from the first deployment night (baseline) over nights two and three, eventually stabilising by the fourth. The other sleep stages were affected similarly, under both cool and warm temperature ranges, with N2 sleep remaining stable over the four nights of the study. Stage N3, slow-wave sleep, or ‘deep

sleep', increased significantly under both temperatures and remained significantly different from baseline night under thermoneutral temperatures. R or REM sleep was also found to increase in both conditions initially, then only over nights three and four. Stage R also increased over the second night of study, although in the heat only. Finally sleep onset latency and wake after sleep onset both decreased, whilst total sleep time and sleep efficiency increased under both temperatures over nights two and three of the study, with all measures comparable to baseline by the fourth night. The conclusion drawn from the first study was that the simulation produced similar effects on the sleep architecture of firefighters in both cool and warm day- and night-time temperatures.

Like Study 1, which provided the first objective scientific data on the sleep architecture of volunteer rural firefighters working and sleeping in both cool and warm temperatures, the effect of continual sleep loss accrued over nights had also been unexplored. Thus, Study 2 provided the first investigation into the sleep architecture of wildland firefighters with partial sleep restriction in either cool or hot temperatures, with daytime physical activity, and a thermoneutral control comparison with full sleep opportunities. The results of Study 2 revealed there were no significant differences on any of the sleep measures between sleep restriction in thermoneutral temperatures and sleep restriction in the heat. Although, sleep restriction under both temperatures did result in significant differences in sleep measures, compared to 8 h complete rest opportunities in temperate conditions. Findings revealed amounts of Stage N1, N2, and R sleep, TST, SOL, and WASO declined whereas sleep efficiency increased by the second night of sleep restriction under both ambient temperatures, when compared to control values. Furthermore amounts of N3 or SWS sleep were stable by the second night of sleep restriction in both sleep restriction temperature conditions relative to the 8 h sleep thermoneutral temperature condition.

The findings of Studies 1 and 2 collectively demonstrate that heat in the range of 33°C to 35°C throughout the daytime and 23°C to 25°C throughout the night-time did not affect sleep architecture any differently compared to day and night-time temperatures of 18-20°C. However, sleep restriction to less than or equal to 4 h per night under the same temperature ranges did have a detrimental effect on the sleep architecture of wildland firefighters when compared to full sleep opportunities of 8 h under both cool and hot ambient temperatures.

Study 3 examined the effect of ambient heat and thermoneutral temperatures with physical activity on hydration status and cognitive performance. This had yet to be quantified either in the field, or the laboratory under controlled conditions, and more importantly in firefighters under any conditions. Hence, Study 3 was designed to provide the first examination of a firefighter's cognitive performance with hydration status resulting from physical tasks carried out in the heat (33-35°C), compared to thermoneutral temperatures (18-20°C) during a laboratory wildfire suppression simulation.

The results of Study 3 showed for cognitive performance on first-order or simple measures such as the PVT, that firefighter's performance on reaction time or lapses was not significantly affected by dehydration compared to normal hydration (i.e., euhydration) in thermoneutral temperatures. However in the heat, firefighters' PVT reaction time and lapse performance was impaired if they were dehydrated. For cognitive measures relying on higher-order or complex executive function, such as reaction times to the non-matching word-pair component of the Stroop task. Results showed that firefighters' performance was impaired late in the day (i.e., approximately 18:00 h) if they were dehydrated, regardless of whether the ambient temperature was cool or hot. Results also revealed a speed-accuracy trade-off for the Stroop task, showing the percentage of correct responses remained stable regardless of firefighters' hydration status, ambient temperature or the time-of-day. Furthermore, for reaction times on the Stroop task component relying on simple or lower-order cognitive functions, results showed that firefighters displayed impairments in cooler temperatures as compared to the heat, in the early- and mid-afternoon testing sessions of the day, regardless of hydration status. In summary, the results of Study 3 indicate that firefighters are at risk of deterioration of simple cognitive functions if they are dehydrated and the temperature is over 32°C. Similarly, for complex mental functions if they are dehydrated and it is very late in the day, regardless of whether the ambient temperature is cool (18-20°C) to neutral, or hot.

Study 3 showed that temperature is a significant stressor for firefighters, and is one that can impact negatively on cognitive performance. It could also result in impaired performance when carrying out physically demanding tasks over a single simulated wildfire suppression work shift. Furthermore, the effects of hot temperatures, sleep restriction, heat, and dehydration have individually been shown to impair cognitive performance, with the exception of physical activity (Cian et al., 2001; Cian et al., 2000; Mazloumi et al., 2014; Van

Dongen, Maislin, et al., 2003). However, it is unknown whether heat and sleep restriction combined with physical firefighter tasks carried out over consecutive days would also result in cognitive performance impairments. No other study either in the laboratory or the field had yet examined the effect of at least two consecutive nights of sleep restriction in the heat with physical activity. Hence, Study 4 was designed to examine the effect of two consecutive nights of sleep restriction in isolation, and also in combination with heat exposure (33-35°C) on firefighters' cognitive performance for tasks assessing simple and complex mental functioning during simulated wildfire suppression.

Study 4 revealed for simple cognitive measures such as reaction time on the PVT that firefighters experienced declines following two consecutive nights of sleep restriction to 4 h, in both cool and warm temperatures. Whilst for PVT lapses, firefighters' performance deteriorated by the first day of sleep restriction in the sleep restriction condition only. Although by the third and final day of the experiment both sleep restriction conditions and also the 8 h *control* condition showed deteriorations in lapse performance. For complex cognitive functions of the Stroop task, firefighters' reaction times on non-matching colour-words had improved in all conditions by the final day of the experiment. However, this was at the expense of accuracy for the sleep restriction and heat condition, with firefighters showing an increase in the percentage of errors. Time-of-day effects revealed firefighters' performance in the morning was impaired relative to the mid- and late-afternoon on baseline and experimental day two, regardless of condition, with an increased percentage of errors for non-matching colour-words. For simple measures of the Go/Nogo task, firefighters' reaction time on correct Go responses, showed a similar pattern as PVT lapses, with declines on the first day of sleep restriction in the sleep restriction condition only. Then by the final experimental day firefighters' Go reaction time performance was impaired in all conditions. For simple functions, firefighters' performance on the percentage of correct Go responses was impaired between the two sleep restriction days in the sleep restriction condition only and also impaired in the morning trial relative to the afternoon trial on all days. Furthermore, for complex executive measures of cognitive function, that is, Stroop inhibitory control, firefighters' performance improved by the final day of the experiment in all conditions. Although interestingly, response inhibition as measured by the Go/Nogo task showed firefighters' performance deteriorated between days of sleep restriction in the sleep restriction and heat condition only.

8.2.1 Implications for temperature and sleep architecture

Scientific data on Australian firefighters' sleep architecture had yet to be examined up until Studies 1 and 2. The results of Study 1 revealed cold temperatures were more disruptive to sleep than the heat, where N1 sleep increased, and R and N2 sleep decreased. Changes in sleep patterns in the heat were similar to the cold but less extensive, with minutes of R sleep significantly reduced at higher temperatures, in addition to slight decreases found in N3 sleep.

The increasing amounts of N1 sleep revealed in Study 1 are in contrast to previous findings from brief (≤ one night) exposures to increasing ambient temperature ranges, which have found that amounts of Stage 1 sleep decrease at low or high temperatures (Bach et al., 2002; Buguet, 2007; Libert et al., 1988). However, the consistent amounts of N2 in the present study compliment earlier findings revealing that amounts of Stage 2 sleep remain consistent during exposure to ambient temperature ranges of 18°C, 24°C, 29°C, 34°C, and 37°C (Libert et al., 1988). The finding that N3 and R sleep increased in both conditions across experimental nights appears to be in contrast to a robust finding from earlier reports of brief exposure studies that as temperature increases SWS and REM sleep decrease (Haskell et al., 1981; Muzet et al., 1983; Muzet et al., 1984; Schmidt-Kessen & Kendel, 1973). This finding may be suggestive of a thermoregulatory mechanism for sleep serving as an "adaptation for energy conservation that offsets the costs of energy expenditure caused by increased muscular activity or thermogenesis during prior wakefulness (Bach et al.. 1994, p. 8)".

Laboratory studies focusing on the effects of high or low ambient temperatures had reported that within a certain range of ambient temperatures referred to as the zone of 'thermoneutrality', sleep quality and quantity are maximal (Bach et al., 2002; Buguet, 2007). Although a thermoneutral zone is often discussed, a specific ambient temperature is rarely defined and tends to vary across studies (Muzet et al., 1983). One study examining the effects of both high and low ambient temperatures ranging from 21°C, 24°C, 29°C, 34°C, and 37°C on sleep architecture identified 29°C as the temperature of thermoneutrality (Haskell et al., 1981) concluding this is point at which temperatures above or below result in more disrupted sleep. Although in contrast the results of Study 1 revealed increased TST, sleep efficiency,

N3 and R sleep in addition to reduced SOL and WASO, compared to baseline, under both thermoneutral and hot temperatures.

These findings may indicate that both temperature conditions displayed comparable patterns of sleep architecture as they appeared on the same side of the quadratic curve of thermoneutrality (lower than 29°C; Haskell et al., 1981). Although, this does not account for sleep measures increasing favourably, as opposed to disruptively by temperatures either side of thermoneutrality (29°C) as previous research would predict (Haskell et al., 1981). It is more likely these results suggest a zone of thermoneutrality was achieved, as research descriptively defines this as the range of temperature where TST, sleep efficiency, SWS and REM sleep will be maximal whilst WASO and SOL will be minimal, as evidenced by the results of Study 1 (Bach et al., 2002; Buguet, 2007). Hence, the results of Study 1 indicate night-time temperatures of 18-20°C and 23-25°C satisfied the conditions of thermoneutrality. These findings suggest the temperature at which thermoneutrality is achieved is lower than 29°C as previously suggested (Haskell et al., 1981) and is actually a range closer to 18-25°C.

Another alternative explanation is research asserts the zone of ‘thermoneutrality’ tends to vary for each study according to bedtime clothing attire and also bedspread covering or ‘bedding’. For example, it has also been found that provided with adequate bedtime clothing and covering (i.e., two cotton sheets and one wool blanket) the microclimate established inside a participant’s bed will remain near constant at 29°C, whilst the ambient temperature fluctuates from 16°C to 25°C (Muzet et al., 1984). This may also explain the results of the present study where participants were provided with sleeping bags so the fluctuations in night-time ambient temperatures from 18-20°C or 23-25°C in the *control* and *hot* conditions, respectively, might not have been sufficient to alter the microclimate established inside the ‘bedding’. Similarly, other evidence for this position is provided from research demonstrating reductions in SWS and REM sleep when bed temperature is raised to 39°C by electric blanket throughout the entire or the second half of the night (Karacan et al., 1978).

The increase in N3 shown in Study 1 over the majority of nights in both cool and warm conditions is also consistent with previous research focusing on daytime temperature manipulations. One reason for the increase in N3 shown in the cool condition and also the warm is that exercise during the day has been shown to promote physical restoration at night associated with an increase in N3 (Horne & Porter, 1975). Furthermore, a series of studies by

Horne and colleagues demonstrated that a high and sustained body heating for one to two hours, with an associated rapid rise in CBT, may trigger a SWS increase response, regardless of the method of induction (Horne & Moore, 1985; Horne & Porter, 1975; Horne & Staff, 1983). That is, ambient heating, warm temperature baths, or intense exercise may simply be a vehicle for this effect. This would also be consistent with the present findings as firefighters performed moderate bouts of self-paced physical activities during the simulated wildland dayshift. The effect of these physical activities, regardless of the ambient conditions of 18-20°C or 33-35°C, may have provided a sustained body heating in CBT and subsequently initiated an increase in N3 in the ensuing sleep episode. That is, it may be that physical activity heats core body temperature, such that external temperature in the range of 33-35°C, has no additional effect on N3 sleep architecture.

8.2.2 Implications for temperature, physical activity, sleep loss, and sleep architecture

The findings of Study 2 revealed significant differences in sleep architecture showing amounts of N1, N2, and R sleep declined from *control* values for sleep restriction in both *control* and *hot* conditions over the two nights of restriction and were comparable to *control* values by recovery night. Furthermore, amounts of N3 remained stable over the two consecutive nights of sleep restriction and recovery, in all conditions. Overall the main finding was that sleep restriction alone is more detrimental to sleep architecture, than either cool or hot ambient temperatures. These results are consistent with previous seminal studies on chronic sleep restriction (Belenky et al., 2003; Van Dongen, Maislin, et al., 2003) reporting that amounts of SWS are relatively conserved, whilst Stage 1, 2 and REM sleep decline.

The findings of Study 2 suggest that sleeping in higher temperatures (23-25°C) at night (18:00 h to 06:00 h) when time in bed is restricted to 4 h, does not result in an adverse effect on sleep architecture compared to sleeping for 4 h in thermoneutral temperatures (18-20°C). This finding is consistent with the results of Study 1 which also demonstrated no differences in sleep architecture following day- and night-time heated temperature manipulations, compared to thermoneutral temperatures. These findings are also consistent with previous research reporting no change in amounts of REM sleep from two nights sleep in temperature ranges from 13-25°C (Muzet et al., 1983). The findings of Study 2 are also consistent with

other research demonstrating a conservation of SWS and REM sleep at baseline measures of 29°C, compared to 21°C for five nights (Palca et al., 1986). However, the findings of Study 2 are in contrast with other research reporting increased amounts of Stage 1 sleep, wakefulness and sleep latency and reduced amounts of Stage 2 sleep and REM, from cold temperatures (defined as 21-24°C; Haskell et al., 1981). Haskell et al. (1981) concluded that an ambient temperature of 21°C provided the most disruptive condition for sleep architecture. However, the results of Study 2 showed reduced amounts of N2 and R sleep with sleep restriction in both temperate (i.e., *control*) and *hot* conditions compared to the baseline night, although the two conditions did not significantly differ on amounts of N2 or R sleep. Hence, any decrease is more likely due to sleep restriction, rather than the experimental manipulation of temperature. Therefore, the results of Study 2 also suggest that night-time temperatures in the range of 18-20°C or 23-25°C may be too narrow to affect night-time sleep. This suggestion would also be consistent with the findings of Palca et al. (1986) reporting no change in SWS and REM sleep from five nights at 21°C compared to 29°C. The effects on sleep may also be more likely to appear at higher temperatures, as shown in research demonstrating increases in SWS and REM sleep at lower room temperatures (27°C) for a single night, compared to increased WASO at higher room temperatures (36°C; Schmidt-Kessen & Kendel, 1973).

The findings of Study 2 also suggest the effects of working during the daytime (06:00 h to 18:00 h) in temperatures of 33-35°C does not adversely affect sleep architecture, compared to working in thermoneutral temperatures of 18-20°C during the daytime with sleep restriction. This finding would appear in contrast to a series of studies reporting that a high and sustained body heating for 1-2 h in the afternoon, may trigger a SWS increase response. Regardless of the method of induction, that is, passive heating (Horne & Staff, 1983), warm temperature baths (Horne & Reid, 1985), or intense exercise (Horne & Porter, 1975).

Furthermore, the findings of Study 2 would also seem to contrast the results of another sleep restriction study (Bach et al., 1994), demonstrating at 20°C for four nights of 4 h sleep, significant reductions in the amount of wakefulness and an increase in Stage 4 sleep compared to 35°C. Furthermore, other research has reported increases in the amount of wakefulness and a reduction in TST and REM sleep at 35°C for five days and nights compared to 20°C (Libert et al., 1988). Alternatively, the findings of Study 2 in one view may actually compliment the findings of previous research, in suggesting that either daytime heating to 35°C and/or physical activity may not be as disruptive to sleep as high night-time

temperatures (35°C) alone. The suggestion that a night-time increase in either ambient temperature or CBT may be more disruptive to sleep than a daytime manipulation is also consistent with previous research (Okamoto-Mizuno et al., 2005). One study reported increases in wakefulness and decreases in SWS sleep, following ambient room temperature increases from 26°C to 32°C during the second half of the nights' sleep (Okamoto-Mizuno et al., 2005).

8.2.3 Implications for temperature, hydration physiology and cognitive performance

Previous research has reported that wildfire suppression poses a significant threat to the hydration status of Australian firefighters (Raines et al., 2015; Raines et al., 2012, 2013). Although until Study 3, the effects of hydration on firefighters' cognitive performance had not been studied in the field or in the laboratory with wildland firefighter suppression activities. Hence, it was important for research to utilise laboratory setting in order to mitigate other potentially confound factors such as natural variations in external temperature, or radiant heat from the environment itself, to assess the effects of dehydration as in Study 3. Furthermore, where literature examining the effects of physical activity and hydration on cognitive performance has been documented in the laboratory, this research focuses on only one stressor in isolation or odd combinations. Additionally, these studies often report contrasting findings possibly due to differences in the levels of dehydration induced. However, Study 3 provided the first quantitative research examining the effects of dehydration induced from physical activity in thermoneutral temperatures, compared to hot temperatures, on cognitive performance.

The aim of Study 3 was to examine the effect of temperate (i.e., *control*) or *hot* conditions, with repeated physical activity sessions throughout the day on the hydration status (i.e., euhydrated or *approaching dehydration*) and cogntitive performance of firefighters in a simulated firefighting environment. Overall, the results demonstrated PVT mean RT remained relatively stable in thermoneutral temperatures regardless of dehydration. Although dehydration in the heat resulted in performance impairments on both PVT mean RT and lapses. These results would suggest that performance on measures of simple, automatic, lower, or first order cognitive processes may be relatively unaffected by dehydration under normal temperatures (Cian et al., 2001; Cian et al., 2000). However in the heat, complex

cognitive functions were associated with performance impairments, particularly later in the afternoon. For the Stroop task, a complex, second-order cognitive process (Cian et al., 2000) Study 3 showed that reaction times for matching word-pairs were significantly affected by condition and time-of-day regardless of hydration level. Hence these results showed impaired performance in normal temperatures and in the heat in both the early-and mid-afternoon testing sessions. However, on non-matching word-pairs reaction times were significantly affected by hydration status and time-of-day, regardless of the temperature with performance most impaired in the dehydrated group by the late afternoon.

The significance of the findings from Study 3 is that for measures of the PVT, dehydration appears to be associated with different outcomes in the heat, as compared to a normative temperature range. For example, PVT mean RT under normal temperatures remained stable regardless of dehydration, however in the heat dehydration resulted in significant impairments relative to both the *hot*- and *control*-hydrated groups and also the *control* dehydrated group. The relatively stable performance on the PVT under thermoneutral temperatures when *approaching dehydration*, contrasts the findings of previous studies reporting that dehydration impairs psychomotor performance regardless of the method of induction (Cian et al., 2001; Cian et al., 2000; Petri et al., 2006; Suhr, Hall, Patterson, & Niinistö, 2004). Potential reasons for differences between studies may be attributed to differences in the level of dehydration. For example in Study 3, a U_{sg} of ≥ 1.020 g·mL^{-1} corresponds to a B_w loss in the range of 3-5% (Popowski et al., 2001), which is actually greater than the 2.8% B_w losses reported in some of the previous studies (Cian et al., 2001; Cian et al., 2000). Although more importantly, the results of Study 3 suggest that it is the addition of heat to dehydration that results in performance deficits on simple or lower-order automatic processes of the PVT. This position would also be consistent with other studies reporting that dehydration in cooler to mild temperatures with physical exercise does not affect cognitive performance (Adam et al., 2008; Leibowitz et al., 1972; Neave et al., 2001; Serwah & Marino, 2006).

Research using numerous methods to induce dehydration has reported that a similar pattern of deficits will generally result for measures of complex cognitive functions when dehydration levels exceed 2% B_m loss (Cian et al., 2001; Cian et al., 2000; Ganio et al., 2011). The results of Study 3 are consistent with this literature. For example, for Stroop RT on non-matching word-pairs, the sub-component of the test relying on the executive function of

response inhibition, hydration status and time-of-day had a significant effect on performance, regardless of temperature. Moreover, for Stroop RT on matching colour-word pairs, the simple sub-component of the test, hydration status did not have a significant effect on performance. Results also revealed for non-matching word-pairs a speed-accuracy trade-off, that is, percentage correct remained stable over the day for both hydrated and dehydrated groups, regardless of temperature, whilst RT became significantly slower in the dehydrated group by the late-afternoon. These findings are consistent with literature reporting a speed-accuracy trade-off, although in the morning results showed an opposite effect with faster reaction times and an increase in errors (Grego et al., 2005; Tomporowski et al., 2007). However, the trend for complex cognitive tasks to decline with dehydration regardless of ambient temperature is not always supported. Numerous studies have reported no effects of dehydration on a variety of complex cognitive tests including the Stroop task when induced by either single (e.g., exercise or heat), or combination stressors (e.g., heat plus exercise) (Armstrong et al., 2012; Grego et al., 2005; Serwah & Marino, 2006; Szinnai et al., 2005; Tomporowski et al., 2007).

8.2.4 Implications for sleep loss, temperature, physical activity and cognitive performance

The importance of Study 4 was that it was the first empirical study to examine cognitive performance on simple and complex cognitive tasks during sleep restriction to 4 h for at least two consecutive nights, in ambient heat with physical activity, in the laboratory. The findings of Study 4 showed PVT mean RRT to decline and lapses to increase over days of sleep restriction which is consistent with findings from previous seminal studies on chronic sleep restriction of seven to 14 nights (Belenky et al., 2003; Dinges et al., 1997; Van Dongen, Maislin, et al., 2003). The findings of Study 4 are also consistent with research employing shorter sleep restriction protocols of 4 h sleep for five nights showing performance impairments on virtually all measures of the PVT, including mean RT, mean RRT and lapses (Banks et al., 2010; Basner & Dinges, 2011; Goel et al., 2014; Haavisto et al., 2010; Philip et al., 2012). Even lesser durations of three consecutive nights of sleep restriction to 4 h have shown consistent increases on PVT mean RT and lapses in a participant sample of women only (Stenuit & Kerkhofs, 2005).

Study 4 also showed that following the first night of sleep restriction, PVT mean RRT significantly declined regardless of ambient temperature and lapses increased in the sleep restriction condition. The day on which performance deficits are observed is not always consistent between studies. For example, Dinges et al. (1997) and Philip et al. (2012) found lapses did not increase significantly until following two consecutive nights of sleep restriction to either 4.98 h or 4 h, respectively. Similarly, other research using acute (i.e., one to two nights) sleep restriction protocols has reported performance declines on PVT mean RT and lapses, only following the second consecutive night of sleep restriction to either 4 h or 4.8 h (Drake et al., 2001; Swann et al., 2006). Furthermore, in contrast, another study reported no effect following two nights of sleep restriction to either 3 h or 5 h on median RT and lapses (Rupp et al., 2004). Whilst consistent with the results of Study 4, two recent studies have shown that sleep restriction to 4 h for a single night resulted in impairments on PVT measures of mean RT and lapses (Innes et al., 2013; Schwarz et al., 2013). As there was an immediate effect on PVT mean RRT and lapses following the first night of sleep restriction shown in Study 4, and since the findings of previous research in the area are equivocal, it seems plausible that sleep restriction with concurrent daytime firefighter physical activities may impact more heavily on PVT performance, than sleep restriction alone.

The findings of Study 4 revealed for the Stroop task the classical ‘Stroop effect’, that is slower response times to non-matching colour-words compared to faster response times to matching colour-words, consistent with previous research (MacLeod, 1991). Study 4 also showed for the Stroop task that median RTs on correct responses to non-matching and matching colour-words improved over the two nights of sleep restriction. These findings are consistent with research from TSD protocols that have shown slower response times on both matching and non-matching colour-word cards 8 h before sleep deprivation on day one compared to 8 h after sleep deprivation on day two (Sagaspe et al., 2006). It could also simply be the observance of a practice effect, suggesting participants develop a reading suppression response through repetitious use of the Stroop task that may potentially mask the effect of sleep loss (Dulaney et al., 1994). However, since the percentage of errors in Study 4 also increased over days of the experiment for both non-matching and matching colour words, this would suggest that participants favoured speed, as if racing to complete a duty, at the expense of accuracy.

The suggestion of a speed-accuracy trade-off for the Stroop task is also consistent with the findings of a previous study using partial sleep deprivation (i.e., less than one night; Tassi et al., 2006). The effect on Stroop task performance of a single nights' partial sleep deprivation to 2 h showed during first half hour of the test participants demonstrated slowed reaction times, while the percentage of errors remained constant. However, during the second half hour of the test, participants adopted a new strategy and the opposite was found, a progressive increase in the percentage of errors whilst response times became faster. This change in strategy for the sleep deprived subjects, where they favoured speed at the expense of accuracy, led the authors to conclude that it was due to the accumulation of fatigue (Tassi et al., 2006).

The findings of Study 4 also demonstrated for Stroop inhibitory control as measured by non-matching minus matching median RTs on correct responses, that all conditions improved by the final experimental day relative to the baseline (Frey, Ortega, Wiseman, Farley, & Wright, 2011). Another important finding was for the *control* condition to continually improve on Stroop inhibitory control performance between days of the experiment that was also revealed slightly for sleep restriction and heat condition, although did not appear in the sleep restriction condition only. Coinciding with these findings on Stroop performance from Study 4, another TSD study using the Stroop task revealed that response times to both matching and non-matching colour-words were stable during the first 14-16 h awake and then in the next 10-12 h, corresponding to habitual sleep time, response times slowed. Performance then stabilised after 24 h awake and remained at a stable level for the remaining 24 h awake, corresponding to the normal waking or working hours of the participants (Cain et al., 2011). This pattern of performance rebound the morning after a night awake has also been observed in many other tasks of cognitive performance and reflects the underlying circadian rhythmicity in the drive for sleep-wake propensity (Blatter & Cajochen, 2007).

Study 4 also found evidence of circadian variation with a time-of-day effect on Stroop inhibitory control. The early-afternoon trial (13:50 h) and mid-afternoon trial (15:50 h) both showed diminished performance relative to the late-afternoon trial (17:50 h). The circadian modulation of Stroop response times have also been reported in studies of forced desynchrony, examining the circadian and homeostatic sleep components affecting cognitive performance (Burke et al., 2015). Results showed that response times for matching and non-matching colour-words were optimal at 21:00 h, with poorer performance obtained at a time

corresponding to 09:00 h, or 1-2 h after awakening, regardless of the homeostatic sleep pressure or level of inertia (i.e., there was no sleep loss). Burke et al. (2015) also found that inhibitory control did not vary with the number of hours awake or increasing homeostatic sleep pressure, although appeared to have a strong circadian modulation. The authors stated that the results could not account for why this measure of executive function remained unimpaired with increasing time awake while other measures of executive functions are affected suggesting the findings implicate a strong circadian role in the modulation of inhibitory control (Burke et al., 2015). Therefore, the idea of circadian modulation of the Stroop task for inhibitory control performance is partly evidenced by forced desynchrony research showing a prominent effect of circadian rhythmicity on inhibitory control performance (Burke et al., 2015). Furthermore studies of complete sleep loss have also shown little to no effect on performance (Burke et al., 2015; Cain et al., 2011; Sagaspe et al., 2012). Moreover, TST research even shows a positive rebound in performance during habitual waking hours, that would seem to implicate performance is determined more so by core temperature, rather than sleep pressure (Cain et al., 2011; Sagaspe et al., 2006).

This suggestion of circadian modulation of performance on the Stroop task may also be consistent with research showing that a single bout of acute exercise, associated with a substantial heating in core temperature, resulted in a significant improvement on Stroop task interference (Hogervorst et al., 1996). Similarly, Study 4 showed physical activity to be a significant co-variate for Stroop inhibitory control and the percentage of errors on non-matching colour-words. This may suggest some facilitatory role of exercise for Stroop function consistent with previous research (Hogervorst et al., 1996; Yanagisawa et al., 2010). Furthermore, it is possible that physical activity may have acted as a stimulus to heat core temperature preceding the cognitive test bout resulting in the stable and sometimes improved response times observed over days of the experiment on both matching and non-matching colour-words for the Stroop task. The increase shown in the percentage of errors on the Stroop task is also suggestive of mental fatigue due to: (one) a high cognitive workload and, (two) physical fatigue from repetitious activity during the simulated dayshifts. This suggestion is provided, as other sleep loss research has previously utilised the Stroop task as a method to induce a high cognitive workload, or mental fatigue, prior to examining other cognitive tests (Goel et al., 2014; Wright, Erblich, Valdimarsdottir, & Bovbjerg, 2007; Wright, Valdimarsdottir, et al., 2007; Yokoi, Aoki, Shimomura, Iwanaga, & Katsuura, 2003, 2006).

The findings of Study 4 showed for the Go/Nogo task that correct response times to Go stimuli slowed on the first day of sleep restriction in the sleep restriction condition only and by the second day of sleep restriction were significantly slower in all conditions. Similar deficits in Go/Nogo performance have been demonstrated in another study on sleep restriction for three consecutive nights in female participants only (Stenuit & Kerkhofs, 2008). Consistent with the results of Study 4 Go/Nogo total response time was shown to slow on the second day of sleep restriction to 4 h relative to baseline (Stenuit & Kerkhofs, 2008). Also in Study 4 findings showed for Go percentage correct that the sleep restriction condition demonstrated impaired performance on the second day of sleep restriction relative to the first. Although in contrast to these findings, the same study by Stenuit and Kerkhofs (2008) reported that the total number of errors (i.e., percentage incorrect) did not show any significant effects from three consecutive nights of sleep restriction to 4 h.

The findings of Study 4 also showed that Go/Nogo response inhibition in the sleep restriction and heat condition demonstrated significantly increased errors by the second day of sleep restriction relative to the first. In contrast, other research on sleep restriction to 3 h for one night using an emotional version of the Go/Nogo task reported no increase in the rate of false alarms (i.e., response inhibition) for responses to fearful faces (Rossa et al., 2014). Similarly, no significant performance impairments on Go/Nogo response inhibition rates have been reported during three consecutive nights of exposure to noise induced sleep disturbances, regardless of an increase in subjective poor sleep quality (Schapkin et al., 2006a, 2006b). Self-rated good (7.2 h TST) and poor (6.7 h) sleepers have also shown no significant differences on performance measures of Go RT, percentage of incorrect Go responses and response inhibition (Nota et al., 2015). The results of these studies imply that Go/Nogo task performance may not be affected by poor sleep or sleep quality, which may also be reflected in the results of Study 4. That is, it may be that sleep amounts of 4 h for only one night do not accumulate enough sleep pressure. As the findings of Study 4 only showed significant differences for performance on Go percentage correct and response inhibition following the second, but not first, night of sleep restriction. Study 4 showed performance for Go percentage correct reached a ceiling effect following the first night of sleep restriction, under low sleep pressure, however, then significant decrements were shown following the second night in the sleep restriction condition only. Similarly, performance on response inhibition showed a comparable trend, suggesting that one night of 4 h sleep is not sufficient to increase

homeostatic sleep pressure to result in performance decrements. Although, following two consecutive nights of sleep restriction, accompanied by an increase in homeostatic pressure for sleep, these deficits may appear, which would appear consistent with previous research on total sleep deprivation (Chuah et al., 2006; Drummond et al., 2006).

The importance of Study 4 is that Go/Nogo performance has been analysed to show how sleep restriction to 4 h, with and without the addition of heat, relative to a normal nights' sleep affects the executive function of response inhibition, as measured by false alarms percentage. Also, automatic responding as indexed by Go RT and Go percentage correct (Drummond et al., 2006; Honma et al., 2015). Specifically, for the executive function of response inhibition, performance deficits were only found in the sleep restriction and heat condition on sleep restriction day two, compared to sleep restriction day one. This suggests the addition of heat to sleep restriction for response inhibition, or executive function, may be more detrimental than increasing sleep pressure alone. Furthermore, where the results of Study 4 present a unique finding for Go/Nogo performance over previous studies of sleep restriction is that Study 4 uses an original Go/Nogo task (Drummond et al., 2006) and not a variant of the paradigm such as an emotional version (Rossa et al., 2014). Additionally, where previous sleep restriction research has reported on the total number of errors across both Go and Nogo stimuli (Stenuit & Kerkhofs, 2008), Study 4 provides a measure consistent with original sleep loss research (Drummond et al., 2006). The present finding of impairments on all Go/Nogo measures, including Go RTs, Go percentage correct and response inhibition, in at least one of the sleep restriction groups over nights of sleep restriction, is more consistent with studies of complete sleep loss (Chuah et al., 2006; Drummond et al., 2006). Go/Nogo task performance impairments on Go correct rates and false alarms (i.e., response inhibition) have been shown after 24 h of TSD (Chuah et al., 2006). Similarly, on the same Go/Nogo task employed in Study 4, impairments in the rate of Go stimuli correct and RTs, along with response inhibition, have been shown after 55.75 h, 31.75 h, and 23 h of TSD, respectively (Drummond et al., 2006).

Time-of-day effects were also found for Go RTs and percentage correct showing by final experimental day that firefighters' performance in the afternoon improved on both measures compared to the morning, regardless of condition. This result is consistent with a previous study showing time-of-day effects on the Go/Nogo task with Go RT performance significantly better at afternoon times of 14:30 h and 16:30 h, as compared to 08:30 h (Petit et

al., 2013). The findings of Study 4 also showed Go percentage correct in the sleep restriction condition had poorer performance in the morning trial compared to the afternoon trial, over days of the experiment. Similar findings have also been shown on the Go/Nogo task with poorer Go RTs being demonstrated in the morning test at 10:00 h following a night of complete sleep loss, as compared to a normal nights' rest (Bougard et al., 2015).

Finally, Study 4 also showed that physical activity did not significantly co-vary with any measures on the Go/Nogo task. This is supported by other exercise research showing Go stimuli RTs and false alarms were not significantly affected following 15 minutes of treadmill running compared to resting conditions (Akatsuka et al., 2015). Similarly, another study showed Go stimuli RTs did not significantly vary following either a low, medium, or high intensity pedalling exercise (Kamijo et al., 2004). Furthermore, it has also been shown that the effect of cycling at a heart rate of 160 beats per minute for 10 minutes in a heated climate of 35°C, did not significantly affect RTs on Go trials compared to rest, or following neck cooling (Ando et al., 2015).

8.3 Practical implications for firefighters and recommendations for fire agencies

From Study 1 it was concluded the effect of either thermoneutral or heated environmental temperatures produced similar effects on sleep architecture for volunteer firefighters, with the findings indicating that sleep architecture will not be adversely affected under these temperatures. From Study 2 it was concluded that the effect of sleep restriction is more detrimental to firefighters' sleep architecture than temperature in itself. This suggestion was based on the observation of significant deteriorations in sleep stages revealed with sleep restriction under both cool and warm temperatures, when compared to full 8 h rest opportunities. Studies 1 and 2 collectively have important implications for managing wildland firefighters during multiple day deployments, as they demonstrate that a firefighter's sleep is relatively safeguarded against working and sleeping in the heat, as well as in thermoneutral temperatures. However, firefighters' sleep architecture will be disrupted significantly from sleep loss, as typically experienced during consecutive nights of wildland fire suppression.

The conclusion that the effect of sleep restriction is a more detrimental stressor compared to temperature on resulting sleep architecture and quantity has important implications for wildland firefighters as the only available research places subjective reports of sleep to between 3 h and 6 h during multi-day fire campaigns (Cater et al., 2007; Gaskill & Ruby, 2004). This is important as sleep restriction and the resulting effects on sleep patterns are associated with significant deficits in daytime mental functioning as measured by cognitive performance, as shown by Study 4 and other research (Belenky et al., 2003; Dinges et al., 1997; Van Dongen, Maislin, et al., 2003).

However, a positive implication arising from the research is the increase in N3 sleep in both cool and warm temperatures with full sleep opportunities as reported in Study 1 and also the maintenance of N3 in both temperature ranges with sleep restriction as reported in Study 2. Although increased N3, as demonstrated in Study 1, does not always imply that physical recovery requirements are completely met, it could be somewhat of an advantage for firefighters faced with physically demanding manual labour, as previous research has indicated that it may also be associated with increased physical restoration (Horne, 1985, 1988; Van Dongen, Rogers, & Dinges, 2003). This is precisely what the results of another study revealed when examining physical task performance, using the same simulation and *control* and *hot* conditions as in Study 1 (Larsen, Snow, Vincent, et al., 2015). Results of this study showed on the simulated self-paced wildland fire suppression tasks (e.g., hose rolling/dragging, and raking) that were no overall differences in work outputs between the control and hot conditions on any of the physical tasks used in the study (Larsen, Snow, Vincent, et al., 2015).

Similarly, the maintenance of N3 across consecutive nights of sleep restriction to 4 h per night as demonstrated in Study 2 is also a positive finding. This is again due to the potential for SWS to be related to physical restitution and potentially safeguard against ensuing physical performance deficits in response to loss (Horne, 1985, 1988; Van Dongen et al., 2003). Again, this is exactly what the findings of another study revealed when examining the effects of sleep restriction on firefighters' physical task performance using the same simulation and *control* and sleep restriction conditions as in Study 2 (Vincent et al., 2015). Results revealed there were no general differences between the sleep restricted and full sleep opportunity conditions on physical work task performance in temperatures of 18-20°C (Vincent et al., 2015).

Similarly, increases in Stage REM sleep have been found to be associated with stable daytime functioning and cognitive performance (Placidi et al., 2000). The decrease in R sleep noted with the concomitant maintenance of amounts of N3 sleep during sleep restriction in Study 2 may have resulted in the preservation of physical work performance, as reported in the study by Vincent et al. (2015). However, stable daytime physical performance may have been at the expense of daytime mental functioning, with declines on measures of cognitive performance demonstrated in response to sleep restriction, as revealed by Study 4. However, prior to discussing the implications of Study 4, it should also be noted that the findings of Study 3 have highlighted a number of important concerns and implications for fire agencies.

Firstly, from the findings of Study 3 firefighters appear to be at risk for deterioration of simple mental functions when dehydrated and ambient temperatures are higher than the range of 23-25°C, particularly if it is late in the afternoon. Secondly, firefighters can be at risk of impaired complex mental functioning, irrespective of external temperatures, if they are dehydrated and it is late in the day (i.e., approximately 18:00 h). This presents a significant risk, as during wildland fires temperatures can reach ranges of 35°C to 45°C (Cheney, 1976). Furthermore, Australian research shows temperatures as low as 26°C can result in sweat loss rates as high as 2.6% of total body mass per hour (Hendrie et al., 1997). Even a single 12 h shift has shown moderate to severe dehydration losses emerging from pre to post measures of B_m (Cuddy et al., 2008; Ruby et al., 2003). Finally, the findings of Study 3 taken collectively with the present research literature (Raines et al., 2015; Raines et al., 2012; Ruby et al., 2003) suggests that fire agency policies regarding the significance of maintaining hydration and the information used to educate personnel are not efficacious or being employed when required as necessary. For example, recent studies of Australian wildland firefighters have shown personnel arrive on shift dehydrated (Raines et al., 2015; Raines et al., 2012) and remain dehydrated over the work shift (Raines et al., 2015). Since dehydration remains a potential heat-related health related concern, fire agencies should continue to ensure regular rest and drinks breaks are provided during wildfire suppression. For fire agencies, hydration status could potentially be improved by increasing the frequency of these rest breaks, in addition to food and fluid provisions along with risk controls such as peer-monitoring, regardless of ambient temperature.

During wildfire deployments firefighters often sleep in poor conditions leading to sleep loss, such as in tents, camp stretchers, or even vehicles (Vincent et al., 2016). Furthermore, they may sleep at home, which means driving to and from the fireground. Hence, firefighters may already initially be at risk of injury or accident on the road, particularly if it is a long commute and the drive is already influenced by sleep loss-related fatigue following a 12 h physical work shift (Vincent et al., 2016). Sleep loss may further be exacerbated the following dayshift, as firefighters often subjectively report the inability to ‘wind down’ easily after their work shift (Vincent et al., 2016). Furthermore there is also the potential of sleep loss and fatigue if firefighters are arriving on shift having come from just completing their regular work hours at their routine employment, since the majority of the wildland firefighting population are volunteers (McLennan & Birch, 2005). Hence given the deterioration in mental functions as shown in Study 4 by cognitive performance impairments due to sleep loss, fire agencies may want to update existing policies on fire days. By modifying criteria such as implementing shorter duration work shifts of less than 12 h in length with quicker crew rotations (Vincent et al., 2016). Furthermore altering sleep locations if possible, for example, to motels or hotel accommodations nearby the fireground, could potentially increase sleep duration and therefore enhance firefighters’ mental functioning during wildfire suppression.

An important contribution to fire agencies of Studies 3 and 4 is that they collectively demonstrate firefighters cannot successfully maintain their mental performance under hot temperatures, whilst carrying out physical tasks and if sleep restricted for multiple days on end (this includes hydration status). This would imply for fire agencies if their crew are sleep restricted and/or in the heat, or even dehydrated in temperate conditions, that the productivity and efficiency of the overall fire suppression operation could potentially decrease. Therefore current deployment practice policies may need to be updated to reflect these findings. Similarly these findings may be used to inform agencies on their shift work structure during wildfire suppression, and could also potentially be extrapolated to other physically challenging occupational settings such as sustained military operations or healthcare providers (for e.g., paramedics and shift-workers such as nurses). For fatigue risk management strategies these results indicate that since sleep loss cannot be avoided and also ambient temperature cannot be controlled, that fire agencies may advance by identifying firefighters at risk of fatigue. This could be implemented with the use of simple mitigation controls, with portable hand held palm devices the PVT program is an easily portable device

for providing cognitive feedback in 5 minutes. The PVT could feasibly be employed to monitor mental performance during a shift and could easily be employed in the field in real-time and provided to workers with addition of work/sleep diaries. Such mitigation controls could represent a potentially valuable addition to existing fire agencies policies on the ongoing monitoring and management of fatigue and also to collect firefighters' recent sleep history.

A positive outcome of Studies 3 and 4 is that they demonstrate under sleep restriction, individually and with hot temperatures, or when dehydrated regardless of ambient temperature, firefighters are able to carry out their duties, albeit at a reduced level of functioning. Also, without any serious heat related illnesses or health concerns, or sleep loss accidents related to fatigue (Larsen, Snow, & Aisbett, 2015; Larsen, Snow, Vincent, et al., 2015). The physical work task protocol utilised in all studies directly reflected the types of varying intensity, work-to-rest ratios and types of fire suppression tasks carried out during fire operations in the field (Phillips et al., 2012; Phillips et al., 2011; Phillips et al., 2007). The frequent rest breaks from physical work provided the opportunities to rehydrate and snack on food, which potentially played a significant role in assisting with the prevention of any fireground related illnesses or injuries whilst faced with harsh environmental and occupational stressors (Larsen, Snow, & Aisbett, 2015; Larsen, Snow, Vincent, et al., 2015). Hence fire agencies should continue to promote policies reflecting the current rest-to-work ratio as it seems that firefighters are able to take frequent enough rest breaks in their present schedule of physical work rotation (Larsen, Snow, & Aisbett, 2015; Larsen, Snow, Vincent, et al., 2015). However, the ongoing observation of wildland firefighter health should also be of continuous importance when working under hot ambient temperatures and/or sleep restriction to monitor and prevent any sleepiness-fatigue related accidents or heat related health concerns.

The findings of Study 3 and 4 may also have implications for how workers' mental productivity is managed throughout the dayshift. Fire agencies policy should reflect the findings that firefighters were unable to maintain stable levels of mental performance when dehydrated in either the heat or cool. Also, over consecutive shifts under sleep loss individually and when combined with heat, but also when no sleep loss or heat was present as shown by the *control* condition. Hence, in order to maintain worker productivity and efficiency during wildland fire suppression it could be expected that the number of

firefighting crews will need to be increased, or faster crew rotations with shorter work periods will need to be employed (Vincent et al., 2016). This would levy the financial costs associated with increased worker numbers against collateral damage to structures, surrounding properties, communities and farmlands. Furthermore, increased worker numbers with faster rotations and additional crews, would only decrease worker exposure to highly toxic fumes of smoke emitted from the fire and the generally hazardous environments of emergency service work such as firefighting.

8.4 Limitations of present research and directions for the future

For agencies it is important to know the effect on sleep architecture of external variations in ambient temperature and consecutive nights of sleep loss as the resulting effects of night-time disturbances in sleep can potentially place individuals at increased risk of error and incident during the daytime (Åkerstedt & Wright, 2009). The strength of the type of experimental design employed in all studies in this thesis is that laboratory simulations allow the isolation of specific effects such as temperature or sleep restriction. Whilst mitigating the effects of various extraneous variables, such as deviations from a specific temperature range, humidity, or wind speed (Lieberman et al., 2006). Furthermore, a second strength of this research was the use of active volunteer firefighters rather than healthy norms. However, future research may also want to focus on applying the use of ambulatory polysomnography and cognitive measures such as the 5 minute palm PVT in the field during multiple-day fire-ground deployments. Data on the sleep architecture and cognitive performance of firefighters during deployments may reveal valuable information from real-time stressors unaccounted for in the laboratory simulations. Another outcome of this data is that it could then be used to validate the reliability and generalisability of findings on sleep architecture from Studies 1 and 2 and also the findings for cognitive performance from Studies 3 and 4 to results obtained in the field. Future research in the laboratory may also introduce and investigate the effects of various other major stressors identified in the field, such as exposure to carbon monoxide, on a firefighter's sleep architecture and cognitive performance.

One potential limitation of Studies 1 and 2 is that it is possible that night-time temperatures in the range of 18-20°C or 23-25°C may be too narrow to affect sleep architecture. Also, these studies used air-conditioners and heat fans that may not aptly simulate other aspects of

temperature experienced in the field, such as wind speed, radiant heat and humidity. This position would also be consistent with previous research demonstrating sleep disturbance are more likely to appear at higher room temperatures (36°C) than at lower ones (27°C; Schmidt-Kessen & Kendel, 1973). Hence future research may also want to consider the impact of intense elevated night-time ambient temperatures (> 25°C) and the effects on sleep architecture during consecutive days of wildfire suppression. Furthermore, quantifying the effect of longer periods of deployments (> four nights) under any conditions, temperate or hot, sleep restricted/ full opportunities, in the either laboratory or the field would be valuable for fire agencies considering wildfires have the potential to burn for weeks (Hunter, 2003; Rodriguez-Marroyo et al., 2012). Additionally, there is a tendency for firefighters to sleep in tents, camp-stretchers and sleeping bags, or vehicels nearby the fireground (Vincent et al., 2016). Although, fire agencies are also noted to occupy nearby air-conditioned motel rooms and accomodations, so there also remains the question as to whether there is a difference between these sleeping conditions on sleep architecture (Jay et al., 2015). Another conceivable limitation of Studies 1 and 2, is the absence of body temperature monitoring, although this was reported by Larsen et al. (2015). Future research may address this limitation of studies 1 and 2 as increases in slow-wave sleep tend to follow body heating in the afternoon and early-evening, as reported by an increase in core body temperature (Horne & Reid, 1985).

Wildland firefighters have been known to suppress fires in temperatures of up 46.4°C, for example the 2009 Black Saturday bushfires, which were also preceded by three days of temperatures exceeding 43°C, prior to the fire igniting (Teague et al., 2010). Since Study 3 showed declines in firefighters' cognitive performance in temperatures of 32-35°C, future research is needed to consider the effect of warmer temperatures on cognitive performance and hydration. This could directly inform fire agencies on predicting the influence of warm conditions on the productivity of their crew and how to best implement fatigue risk management strategies. Furthermore, future research measuring changes in body mass to approximate the level of dehydration, as is standard in the sports-science laboratory literature, should take into account the inherent limitations of this measure (Cheuvront et al., 2010). As a combination of body mass and U_{SG} data provides the most accurate status of hydration and this should also be highlighted in retrospect for firefighters in Study 3 (Cheuvront et al., 2010). Although, there has been some debate regarding dehydration assessment in recent studies, for their alternative views the reader is referred to Armstrong et al. (2013) and

Cheuvront, Kenefick, and Charkoudian (2013). Another conceivable limitation of Study 3, and also Study 4, is that repetitious use of the Stroop task can result in a practice effect that may lead participants to develop a reading suppression response and could potentially mask the effects of sleep restriction (Dulaney et al., 1994; Sagaspe et al., 2006). However, had participants adopted this strategy it would be expected that non-matching and matching trial RTs would not differ significantly (Cain, 2011). However, results showed RTs were longer for non-matching compared to matching trials, consistent with the standard Stroop effects (MacLeod, 1991), and indicate that performance on the task continued to require inhibitory control.

In the United States, studies on wildfire suppression have shown fires can burn for up to two consecutive weeks with firefighters undergoing deployments as long as 14 consecutive days (Heil 2002; Ruby et al., 2002; Ruby et al., 2003). It is a probability that either the length of sleep restriction with only two nights, or the duration of time in bed at 4 h, used in Study 4 was not long enough to produce an adverse effect on firefighters' performance on some of the higher order executive cognitive measures. The duration of all studies in this thesis reflected Australian deployments that typically occur for three to five days (Cater et al., 2007; Phillips et al., 2007). However future research on the effects of longer-term wildfire suppression deployments is warranted to inform on the effects on firefighters' cognitive performance and sleep architecture. This could be achieved either in the laboratory or the field with prolonged sleep restriction periods greater than two nights and also with variable sleep durations that are more severe (for e.g., 3 h per night), and/or reflective of findings of sleep loss for firefighters in the field (i.e., 6 h; Vincent et al., 2016).

While simulations allow for the examination of wildfire scenarios in a safely controlled laboratory, it may also be suggested that the strength of this type of experimental design is the inherent limitation, as an artificial environment is not a perfect recreation of fire suppression conditions in the field (Larsen, Snow, Vincent, et al., 2015; Larsen, Snow, Williams-Bell, et al., 2015). For example, one conceivable limitation of safely controlled laboratory simulations is the absence of urgency that is created under the circumstances of an emergency or presence of danger that is never far away during wildfire suppression (Larsen, Snow, Vincent, et al., 2015). Similarly, wildland firefighters experience other hazards on the fireground that were not simulated in the present studies such as loud noises from vehicles, and machinery or exposure to flames, smoke, carbon dioxide and other natural gases that may

cause harm, discomfort or irritation (Aisbett et al., 2012). Nonetheless, it should be noted that in conceiving the design for the present studies, the tasks employed were primarily chosen to reflect those commonly performed preparing or planning for the wildfire before it commences or after the fire front has moved through (Larsen, Snow, Vincent, et al., 2015; Phillips et al., 2012). For example, clearing natural combustible fuels such as leaves or shrubbery with rake hoe work (Larsen, Snow, Vincent, et al., 2015; Phillips et al., 2012). More importantly, wildfire suppression in the field is not always composed of directly attacking the fire, as such physical tasks were also selected that are typically performed away from the fire-front, for example the rolling of fire hoses (Larsen, Snow, Vincent, et al., 2015; Phillips et al., 2012). Hence, wildfire suppression is not always performed under the presence of danger or urgency, even when in an operational environment.

Similarly another conceivable limitation of Studies 1,2, 3 and 4 is that the present data could underestimate the thermal stressors of real wildland firefighting for personnel when they are in the field, such as radiant heat from the fire itself, or high wind speeds, that were not simulated in the present studies (Larsen, Snow, Vincent, et al., 2015; Larsen, Snow, Williams-Bell, et al., 2015). However, as noted there is a common misconception that firefighters are always on the fire-front with suppression operations often occurring far away from the fire itself, in order to contain or prevent the fire from spreading (Budd et al., 1997). Additionally, for Study 3 high wind speeds in the field could potentially result in a greater rate of an evaporative cooling effect on hydration status, however, the personal protective clothing firefighters are required to wear is known to significantly impede convective heat losses (Barr et al., 2010). Therefore any difference between simulated and real wildfire environments may only be relatively diminutive in their effects on sleep architecture, hydration, and/or cognitive performance (Larsen, Snow, Vincent, et al., 2015; Larsen, Snow, Williams-Bell, et al., 2015).

For Studies 1, 2, 3, and 4, the use of active volunteer firefighters could underestimate the effects of sleep restriction, temperature, dehydration and physical activity, on cognitive performance and sleep architecture, compared to non-firefighters. This potential limitation is raised, as it could be likely as firefighters regularly undergo exposure to these types of stressors they may have developed a stronger tolerance to these working conditions compared to individuals who do not work in these types of conditions. Although, a survey of Country

Fire Authority first year volunteers (McLennan & Birch, 2005), suggests that there is nothing demographically unique or specialised about this population in terms of age or body mass index, that would prevent the generalisabilty of the results for Studies 1, 2, 3, and 4, to non-firefighting populations. Although as with any research, generalisability of results should always be cautiously interpreted, when comparing to other working conditions, or types of occupations, as this may be problematic, for example due to differences in physical or mental workload.

Within Australia communities are safeguarded from the threat of wildfires by an estimated 220,000 volunteer firefighters, both male and female, ranging in age from 18 to 65 years, all with a highly variable level of fitness and years of experience in the field (McLennan & Birch, 2005). The studies in this thesis used an advanced linear mixed model statistical procedure to account for differences between firefighters, such as age or gender, as covariates (Dorrian, Hussey, et al., 2007; Dorrian et al., 2006; Dorrian, Roach, et al., 2007). Although, while the purpose of this thesis was not intended to inform on the effects of demographic factors on firefighters' performance, it has been shown that age, sex, BMI and/or physical fitness can influence cognitive performance and sleep architecture (Falkenstein et al., 2002; Horne & Porter, 1975; Horne & Staff, 1983; Stenuit & Kerkhofs, 2005; Stroth et al., 2009; Voyer, Voyer, & Bryden, 1995; Yesavage et al., 2014). Hence, in the future fire agencies may want to consider the role of demographic characteristics in their workers and how these individual differences may influence cognitive performance and sleep architecture in the wildland firefighting population. This also may allow fire agencies to implement policies and workplace strategies personalised to best suit an individual's needs, for example, this may be as simple as assigning firefighters over a certain age to tasks that are less physically demanding. For example, should volunteer firefighters have existing sleep difficulties or problems such as sleep apnoea, or are older and less physically fit than a healthy younger volunteer, then fire agencies may want to consider their delegation of roles when it comes to more physical tasks.

Future research may specifically want to examine age-related changes in firefighters' sleep architecture and cognitive performance under conditions of sleep loss, heat, dehydration and physical activity. As previous research shows age modulates the effects of: circadian rhythms, sleep quality and quantity (Dijk et al., 2000); sleep restriction on cognitive performance (Stenuit & Kerkhofs, 2005); hydration status and cognitive performance (Suhr, Hall,

Patterson, & Niinisto, 2004); sleep loss and executive function on Go/Nogo task performance (Sagaspe et al., 2012); sleep loss and vigilance (Adam, Retey, Khatami, & Landolt, 2006) . For example, the effects of 4 hours sleep restriction for three nights on the cognitive performance of a sample of younger women aged 20 to 30 years compared to women aged 55 to 65 years, showed older women were more resilient to the effects of sleep restriction as shown by performance on a vigilance task (Stenuit & Kerkhofs, 2005). Hence, future field and laboratory research examining the effects on cognitive performance or sleep architecture under conditions of sleep restriction, heat, physical activity or dehydration may also want to consider age-related differences by comparing individuals' under a certain age, for example under 45 years to 45 years and over.

Wildfire suppression requires 24 h round the clock operations to be carried out by firefighting crews in order to protect against damage to property and the potential loss of life (Aisbett et al., 2012; Cater et al., 2007). However, all of the studies in this thesis are focussed on daytime operations from 06:00 h to 18:00 h. Currently there is no available literature examining cognitive performance or sleep physiology during wildfire suppression work carried out in the late hours of the evening and early hours of the morning from 18:00 h to 06:00 h, during 12 h nightshifts on deployments. Hence fire agencies and future research may also want to examine wildfire suppression operations carried out during the night to better understand the effects of shift structure on sleep architecture, hydration status and cognitive performance. This could very easily be implemented by firefighters performing the same laboratory simulation as in Studies 1, 2, 3 and 4, although substituting day-time for night-time, or split day-and night-time sleeps.

In conclusion, the studies presented in this thesis demonstrate how the occupational and environmental stressors that firefighters face during wildland fire suppression such as temperature, physical activity, dehydration and sleep restriction can all result in impairments to sleep architecture and cognitive performance. Fire agencies may want take note of the results reported by the studies in this thesis to update their existing policy guidelines and recommendations regarding sleep loss, temperature and dehydration with scientific based research. Furthermore, using some of the mitigation and safety controls discussed in this thesis could allow fire agencies to potentially increase or maximise worker safety, physical productivity, and mental efficiency during wildfire suppression operations. To better inform fire agencies in the future, laboratory and field research should focus on the effects on

firefighters sleep and cognitive performance of more extreme ambient temperatures, both hot and cold, with greater amounts of sleep loss, for prolonged periods of time, such as a week or more.

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Appendices

Appendix A: Central Queensland University Human Ethics Research approval letter

Secretary, Human Research Ethics Committee
Ph: 07 4923 2603
Fax: 07 4923 2600
Email: ethics@cqu.edu.au

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Rockhampton QLD 4702
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Dr Sally Ferguson
C/- Centre for Sleep Research
University of South Australia
GPO Box 2471
Adelaide SA 5001

7 February 2012

Dear Dr Ferguson

HUMAN RESEARCH ETHICS COMMITTEE ETHICAL APPROVAL PROJECT: H12/01-016
AWAKE, SMOKY & HOT: WORKPLACE STRESSORS WHEN FIGHTING BUSHFIRES

The Human Research Ethics Committee is an approved institutional ethics committee constituted in accord with guidelines formulated by the National Health and Medical Research Council (NHMRC) and governed by policies and procedures consistent with principles as contained in publications such as the joint Universities Australia and NHMRC *Australian Code for the Responsible Conduct of Research.*

On 7 February 2012, the Chair of the Human Research Ethics Committee of CQUniversity considered this project, under the provisions of chapter 5.3 of the National Statement (minimising duplication of ethical review). The project has received prior approval from the Deakin University HREC (Protocol number 2010-170) in the name of Dr Brad Aisbett.

It is advised that CQUniversity HREC accepts this determination, and hereby extends full clearance as a CQUniversity project **(Project Number H12/01-016)** please quote this number in all dealings with the Committee. The period of ethics approval will be from 7 february 2012 to 31 August 2014.

The standard conditions of approval for this research project are that:

(a) you conduct the research project strictly in accordance with the proposal submitted and granted ethics approval, including any amendments required to be made to the proposal by the Human Research Ethics Committee;

(b) you advise the Human Research Ethics Committee (email ethics@cqu.edu.au) immediately if any complaints are made, or expressions of concern are raised, or any other issue in relation to the project which may warrant review of ethics approval of the project. *(A written report detailing the adverse occurrence or unforeseen event must be submitted to the Committee Chair within one working day after the event.)*

(c) you make submission to the Human Research Ethics Committee for approval of any proposed variations or modifications to the approved project before making any such changes;

Central Queensland University CRICOS Provider Codes: QLD - 00219C, NSW - 01315F, VIC - 01624D

(d) you provide the Human Research Ethics Committee with a written "Annual Report" on each anniversary date of approval (for projects of greater than 12 months) and "Final Report" by no later than one (1) month after the approval expiry date; *(A copy of the reporting pro formas may be obtained from the Human Research Ethics Committee Secretary, Sue Evans please contact at the telephone or email given on the first page.)*

(e) you accept that the Human Research Ethics Committee reserves the right to conduct scheduled or random inspections to confirm that the project is being conducted in accordance to its approval. Inspections may include asking questions of the research team, inspecting all consent documents and records and being guided through any physical experiments associated with the project

(f) if the research project is discontinued, you advise the Committee in writing within five (5) working days of the discontinuation;

(g) A copy of the Statement of Findings is provided to the Human Research Ethics Committee when it is forwarded to participants.

Please note that failure to comply with the conditions of approval and the *National Statement on Ethical Conduct in Human Research* may result in withdrawal of approval for the project.

You are required to advise the Secretary in writing within five (5) working days if this project does not proceed for any reason. In the event that you require an extension of ethics approval for this project, please make written application in advance of the end-date of this approval. The research cannot continue beyond the end date of approval unless the Committee has granted an extension of ethics approval. Extensions of approval cannot be granted retrospectively. Should you need an extension but not apply for this before the end-date of the approval then a full new application for approval must be submitted to the Secretary for the Committee to consider.

The Human Research Ethics Committee wishes to support researchers in achieving positive research outcomes. If you have issues where the Human Research Ethics Committee may be of assistance or have any queries in relation to this approval please do not hesitate to contact the Secretary, Sue Evans or myself.

Yours sincerely,

Professor Phillip Ebrall
Chair, Human Research Ethics Committee

Cc: Dr Brad Aisbett, Ms Katrina Onus, Ms Cara Lord (Partner investigators from Deakin University),
Dr Sarah Jay
Project file

APPROVED

Appendix B: Recruitment flyer 1

Awake, Smoky & Hot:

Workplace stressors when fighting bushfire

We need volunteer firefighters (18-65) to be part of our research study

Do you ever feel sleep deprived, heat stressed or the effects of smoke while on the fireground? Take part in a multi-day (72 h) fireground simulation which aims to capture task performance, physiology, cognition, and sleep quality under different environmental conditions. Information on your usual sleeping patterns will be collected both pre- and post-testing. Participants will be required to 'live' in our simulated testing environment at either Box Hill Town Hall, Melbourne or Brukunga, Adelaide for four nights.

If you are interested in participating or finding out more information, please contact **Brad Smith** at Central Queensland University

b.p.smith@cqu.edu.au

08 8378 4528

Funded by the Bushfire CRC and conducted by researchers at Deakin and Central Queensland University, and the CSIRO

You can also register your interest online http://tinyurl.com/awakesmokyhot

All participants are encouraged to consider a medical check before participating

CQUniversity AUSTRALIA

DEAKIN Worldly

Appendix C: Recruitment flyer 2

Awake, smoky and hot: Workplace stressors when fighting bushfires

We need CFS Volunteers be part of our project

We are interested in how environmental stressors such as heat, smoke and lack of sleep contribute to performance and safety when on the fire-ground.

We are looking for CFS volunteers to take part in a fire-ground ‘simulation’ capturing the performance of tasks (mental, including reaction time and memory and physical, including hose rolling, raking and hose dragging and repositioning) and sleep of volunteers across consecutive shifts (72 h). Sleep and awake information will be collected before, during and after the simulation experience.

Participants will be required to ‘live’ in our simulated environment at the CFS Training College in Brukunga for four nights and we are seeking volunteers to take part from either;

[insert date]

All participants are encouraged to consider a medical check before participating.

If you are interested in participating or finding out more information, please contact **Sally Ferguson** at Central Queensland University

sally.ferguson@unisa.edu.au or 0407 799 204

This research is being funded by the Bushfire CRC and conducted by researchers at Central Queensland University, Deakin University and the CSIRO.

The CFS is in full support of this research

Appendix D: Plain language statement participant information sheet

PLAIN LANGUAGE STATEMENT AND CONSENT FORM

TO: Participant

Plain Language Statement

Date:

Full Project Title: Awake, smoky and hot: workplace stressors when fighting bushfires

Principal Researchers: Dr Brad Aisbett (Deakin University)
Associate Professor Sally Ferguson (CQUniversity)
Dr Sarah Jay (University of South Australia)

Associate Researcher(s): Dr Brad Smith (CQUni)
Mr Michael Crvin (CQUni)
Miss Madeline Spracjer (CQUni)
Miss Cara Lord (Deakin University)
Miss Brianna Larsen (Deakin University)
Miss Grace Vincent (Deakin University)
Mr Alex Wolkow (Deakin University)
Mr Daniel Neesham-Smith (Deakin University)
Miss Sarah Jefferies (Deakin University)
Dr Luana Main (Deakin University)
Dr Kevin Netto (Deakin University)

Purpose:

The purpose of the proposed research is to investigate the individual and combined effects of heat, smoke and sleep restriction on firefighter performance during a simulated fireground tour.

Methods:

Participation in this project will involve a three-day campaign fire simulation at Fiskville (Victorian State Training Centre). You will arrive by 1800 the first evening having kept a record of your sleep/wake/work patterns (by wearing a small monitor on your wrist and filling in a sleep diary) for the previous week. You will then spend the next four nights at the facility and undertake physical work tasks and computer-based tests every two hours during three, simulated, day-time shifts. During this time we will measure your blood pressure using an automated blood pressure machine, your level of dehydration (through assessment of your urine colour and concentration) and the volume of urine, your blood glucose (sugar) levels via a small fingertip sample of your blood and your stress hormones, through chewing on a cotton swab until it's very soggy and then spitting it into a tube. We will also assess your lung function which will involve breathing powerfully into a small machine; grip strength, where you will grip a machine as forcefully as you can; static balance, where you will stand on one leg on a force platform, and then switch to the other; dynamic balance, which will involve you stepping from a box onto a target on the floor and carbon monoxide exposure via two methods 1) breathing into a second type of machine and 2) having a fingertip oximiter attached to your finger for about a minute. Each sleep will be measured using a standard sleep recording procedure which requires small wires to be attached to your head and face. In addition, you will be asked to rate your effort, thermal sensation, motivation, feelings of hunger and food cravings at set times throughout the simulation. Following the simulation you will spend a 'recovery' night at the traning college this will be followed by another 2 h bout of physical and computer-based testing before going home at approximaltey 1100 on Day Five. Prior to leaving the facility you will complete a one on one interview with a researcher (no longer than 15 min duration) about your experiences during the testing period. Finally, in the week following you will continue to record information about your sleep (timing, duration, quality) using the wrist monitor and sleep diary. You will participate in groups of five and be randomly allocated to one of eight different conditions involving various combinations of high heat, raised carbon monoxide levels and reduced total sleep time.

Demands:

The proposed research has been designed to approximate the demands placed on firefighters during suppression of multi-day bushfires. For this reason, you will be exposed to intermittent physically hard work, and cognitive tasks which challenge your attention, concentration and memory. Further, depending on the trial you participate in, you could be

exposed to high day-time temperatures, raised levels of carbon monoxide, or reduce sleep opportunities. Each of these environmental stressors is based on real fireground conditions.

In order to effectively assess your responses (physical, cognitive, subjective and physiological) to the experimental conditions you will be required to 'live' in the simulated environment and adhere to a strict schedule as dictated by the protocol. This means you will be instructed when to eat main meals, sleep and perform physical/cognitive task at specific times throughout each day. While cigarettes and caffine will be permitted, you will be asked to consume them as you would during campaign bushfire suppression - this might mean smoking/drinking less than you would on a regular day. You will not be permitted to leave the facility nor will you be able to have visitors where you are there. You will however be able to maintain contact with family and friends through your mobile phone during non-testing times.

All food and drink will be provided for you during your visit, please do not bring your own food or drink onsite. If you have particular dietary requirements, please advise the researchers when you return your consent and medical forms to enable us to cater for you.

Potential risks to participants:

You will be performing strenuous physical exercise which has inherent risks such as musculoskeletal injury, heat stress, and sudden cardiac death. The risks are, however, very small due, in part, to the medical screening procedures used in the study where individuals with current musculoskeletal injuries or two or more risk factors for cardiovascular disease will be asked to seek medical authorisation before commencing testing. **All participants are encouraged to consider a medical check before participating in the research.** Further, the likelihood of these risks occurring is extremely low as the testing you will be undertaking is based on "real" work practices which you perform routinely when striving to curtail the spread of bushfire.

Exposure to hot working conditions can lead to heat stress, however, the conditions are similar to those faced during real fireground working conditions and as per fire agency guidelines, you will be provided with free access to food and fluid to manage your hydration status and limit your heat stress. Exposure to low levels of carbon monoxide (such as those proposed in this study) can be associated with headaches, dizziness and confusion. The current study will, however, be only using carbon monoxide levels that are consistent with those experienced on the fireground and are within Occupational Health and Safety guidelines for Australia and the United States of America. The levels of sleep restriction proposed for the current study are similar to those reported by firefighters during bushfire suppression. Though partial sleep deprivation is associated with impaired cognitive function which can lead to an increase in errors, your behaviours when partially sleep deprived will be closely monitored by the research team to ensure such errors do not lead to injury.

Expected benefits to wider community:

Research dedicated to understanding the impact that firefighters' working environment, namely temperature, air composition, and sleep periods is fundamental if fire agencies are going to implement policies to preserve the health and safety of their crew. The proposed research will provide an evidence-based from which Australian firefighting agencies can make informed decisions about management of risk associated with firefighters' work hours, workload and working conditions.

Privacy and confidentiality:

Your privacy and confidentiality will be preserved through a number of measures. Firstly, your interest and participation in, or withdrawal from will be largely anonymous. As you wll be performing your testing within small groups of five, the other four members of your testing may, should you introduced yourself, know your identity. We ask, however, that all participants do not disclose the identity of any other participant without that individual's explicit consent. We will re-iterate the need to gain consent for revealing the identity of any other individual participant before testing commences. Secondly, your results and identity will be stored separately, such that the researchers will only refer to your data by your unique identifier code. Your data will be stored securely for a period of six years after the final publication of results, as per University guidelines. Thirdly, should you choose to withdraw from the research, your data and personal records will be destroyed immediately after receipt of your revocation of consent form (attached). Fourthly, your fire agency will have no record of your decision to participate in, or withdraw from the proposed research.

Dissemination of the research results:

The results from the proposed research will be presented in either a) oral presentation to fire industry or scientific audiences, b) written, peer-reviewed scientific journal articles, or c) Bushfire Co-Operative Research Centre (CRC) Firenote research briefings. In each case, only mean results will be reported and, as such, no individual results or identities will be revealed.

Research monitoring:

All research will be monitored by principal investigators Dr Brad Aisbett, Associate Professor Sally Ferguson and Dr Sarah Jay.

Payments to participants:

You will not be paid for your participation in the proposed research.

Sources of research funding:

The proposed research is funded by the three-year extension to the Bushfire CRC. Specifically, the project is part of the Occupational Health and Safety project, within the Managing the Threat program of the Bushfire CRC extension. The Bushfire CRC extension is funded by the Federal Government and by cash and in-kind contributions from organizations that form the Australasian Fire Authorities Council.

Should you have any questions, please contact

Dr Brad Aisbett
School of Exercise and Nutrition Sciences
Deakin University
Burwood VIC 3125
Phone: 03 9244 6474 Fax: 03 9244 6017 Email:
brad.aisbett@deakin.edu.au

Complaints

If you have any complaints about any aspect of the project, the way it is being conducted or any questions about your rights as a research participant, then you may contact:

The Manager, Office of Research Integrity, Deakin University, 221 Burwood Highway, Burwood Victoria 3125, Telephone: 9251 7129, Facsimile: 9244 6581; research-ethics@deakin.edu.au

Please quote project number [2010-170].

Appendix E: Participant consent form

PLAIN LANGUAGE STATEMENT AND CONSENT FORM

TO: Participants

Consent Form

Date:

Full Project Title: Awake, smoky and hot: Workplace stressors when fighting bushfires

Reference Number: [2010-170].

I have read and I understand the attached Plain Language Statement.

I freely agree to participate in this project according to the conditions in the Plain Language Statement.

I have been given a copy of the Plain Language Statement and Consent Form to keep.

The researcher has agreed not to reveal my identity and personal details, including where information about this project is published, or presented in any public form.

I give my specific consent to be filmed throughout testing and understand that the researchers may contact me again for my data to be used for other research purposes.

Participant's Name (printed) ……………………………………………………………………

Signature …………………………………………………… Date …………………………

Should you wish to return your consent form (and have lost your reply-paid envelope), please send the forms to:

Dr Brad Aisbett

School of Exercise and Nutrition Sciences

Deakin University

Burwood VIC 3125

Phone: 03 9244 6474 Fax: 03 9244 6017 Email:

brad.aisbett@deakin.edu.au

PLAIN LANGUAGE STATEMENT AND CONSENT FORM

TO: Participants

Revocation of Consent Form

(To be used for participants who wish to withdraw from the project)

Date:

Full Project Title: Awake, smoky and hot: Workplace stressors when fighting bushfires

Reference Number: [2010-170].

I hereby wish to WITHDRAW my consent to participate in the above research project and understand that such withdrawal WILL NOT jeopardise my relationship with Deakin University or Country Fire Authority.

Participant's Name (printed) …………………………………………………….

Signature ……………………………………………………………….. Date ……………………

Please mail or fax this form to:

Dr Brad Aisbett
School of Exercise and Nutrition Sciences
Deakin University
Burwood VIC 3125
Phone: 03 9244 6474 Fax: 03 9244 6017 Email:
brad.aisbett@deakin.edu.au

Appendix F: Medical screening and General Health Questionnaire

Awake, Smoky and Hot Screening Questionnaire

Occupational and environmental factors impacting firefighter performance

Name____

1 What is your age?____________ years

2 Gender: Male ☐ Female ☐

3 Domestic status:

Married / Living with a partner ☐

Separated / Divorced ☐

Widowed ☐

Single ☐

4 Do you have children living at home with you? Yes ☐ No ☐

5 If yes, how many? ______ and how old are they? 1)_______ 2)_______ 3)_______ 4)_______ 5) _______

6 Do you consume caffeinated products (eg coffee, tea, cola, energy drinks, chocolate bars etc)?

Yes ☐ No ☐

If YES, adding all of these together, how many items do you normally consume each day?

____

7 Do you describe yourself as a:

☐ Regular smoker
(I smoke one or more cigarettes per day)

☐ Occasional smoker
(I do not smoke every day)

☐ Ex-smoker
(I used to smoke but not anymore) regularly)

☐ Non-smoker
(I have never smoked

8 How often do you drink alcohol?

☐ Never ☐ Less than once per week ☐ Once or twice per week ☐ Once every two days ☐ Daily

9 On a typical drinking occasion, how many drinks do you have? (One drink equals a glass of beer, a glass of wine or a shot of liquor).

☐ None ☐ Less than 2 drinks ☐ 2-4 drinks ☐ 5-6 drinks

10 Have you travelled overseas in the last four weeks? ☐ No ☐ Yes

If YES, when and where did you travel?

____

WORK

11 Are you, or have you ever been, involved in shift work? ☐ Yes ☐ No

If YES, when were you involved in shift work, and for how long?

____

____

______

12 Are you currently employed? ☐ Yes ☐ No

If YES, what is your current occupation?

____

13 How often do you work?

☐ Full-time ☐ Part-time ☐ Casual ☐ Seasonal ☐ Self-employed

FIREFIGHTING HISTORY

14 Years of fire fighting experience (volunteer and/or salaried)?____

15 How long have you been a member of the CFS?____

16 What training have you completed?____

____

______

17 Approximate number of campaign deployments? ________________________

18 When were you last called for a job to which you responded/attended?

____

HEALTH

19 *Do you have a history of:*	Yes	No	Don't know
Serious accident, head injury or concussion?	☐	☐	☐
Epilepsy or other neurological disorders?	☐	☐	☐
Unexplained loss of consciousness?	☐	☐	☐
Migraine headaches?	☐	☐	☐
Respiratory problems?	☐	☐	☐
Chronic depression or another psychiatric problem?	☐	☐	☐
Cardiovascular disease (e.g. heart attack, stroke)?	☐	☐	☐
Substance abuse?	☐	☐	☐
Recreational drug use?	☐	☐	☐

20 *Has anyone ever told you that you?*	Yes	No	Don't Know
Are overweight?	☐	☐	☐
Have high blood pressure?	☐	☐	☐
Have a heart murmur?	☐	☐	☐
Are asthmatic?	☐	☐	☐
Are diabetic?	☐	☐	☐

21 *Have you ever had?*	Yes	No	Don't Know
Chest pain, chest discomfort, chest tightness or chest heaviness?	☐	☐	☐
Shortness of breath out of proportion to exercise undertaken?	☐	☐	☐
Sensations of abnormally fast and/or irregular heart beat?	☐	☐	☐
Episodes of fainting, collapse or loss of consciousness?	☐	☐	☐
Abnormal bleeding or bruising?	☐	☐	☐

If you answered 'yes' to any parts of Questions 20, 21 and 22 above, please provide details regarding any restrictions
or cautions that may need to be taken during the course of the study.

____

____

____

____

22 Have you ever suffered any musculoskeletal injury or had a disorder that has impaired your movement or functioning?

☐ Yes ☐ No ☐ Don't Know

If YES, please elaborate:

____

____

____

23 Do you have a cardiac pacemaker or other implanted electro-medical device?

☐ Yes ☐ No ☐ Don't Know

If YES, please elaborate:

____

____

____

24 Are you currently taking any medications? ☐ Yes ☐ No

If YES, please list the medications

____

______

____

_____

____

_____

25 Do you have any allergies (e.g. to any food, tapes or bandaids (adhesives), latex etc)

If YES, please list the allergies

____

______

____

_____

26 Will you be having a medical procedure or travelling by aeroplane in the next month?

☐ Yes ☐ No ☐ Don't Know

SLEEP

27 How many hours of sleep do you need to feel rested? _____________ hours

28 How satisfied are you with the amount of sleep you get?

Very dissatisfied 1 2 3 4 5 6 7 8 9 10 Very Satisfied

29 Overall, how would you rate the quality of your sleep?

☐ very poor ☐ poor ☐ fair ☐ good ☐ very good ☐ excellent

30 Have you ever been diagnosed with a sleeping problem? ☐ No ☐ Yes

If YES, please describe

____

____

____

31 How often do you take naps? (e.g. never, occasionally, once a day, twice a week)

____

32 *How likely are you to doze off or fall asleep in the following situations, in contrast to feeling just tired?* (This refers to your usual way of life in recent times. If you have not performed a listed activity, make a guess at what you are likely to do during that activity). PLEASE TICK ONE BOX PER LINE

	Would never doze	Slight chance	Moderate chance	High chance
Sitting and reading	$_0$☐	$_1$☐	$_2$☐	$_3$☐
Watching TV	$_0$☐	$_1$☐	$_2$☐	$_3$☐
Sitting inactive in a public place (eg theatre, meeting)	$_0$☐	$_1$☐	$_2$☐	$_3$☐
As a passenger in a car for an hour without a break	$_0$☐	$_1$☐	$_2$☐	$_3$☐
Lying down in the afternoon when circumstances permit	$_0$☐	$_1$☐	$_2$☐	$_3$☐
Sitting and talking to someone	$_0$☐	$_1$☐	$_2$☐	$_3$☐
Sitting quietly after lunch without alcohol	$_0$☐	$_1$☐	$_2$☐	$_3$☐
In a car, while stopped for a few minutes in traffic	$_0$☐	$_1$☐	$_2$☐	$_3$☐

33 *Please answer the following in relation to sleep timing*

- Please read each question very carefully before answering.
- Please answer each question as honestly as possible.
- Answer ALL questions
- Each question should be answered independently of others. Do NOT go back and check your answers.

  - What time would you get up if you were entirely free to plan your day?

    5:00 – 6:30 AM ☐
    6:30 – 7:45 AM ☐

7:45 – 9:45 AM ☐
9:45 – 11:00 AM ☐
11:00 – 12 Noon ☐
12 Noon – 5:00 AM ☐

- What time would you go to bed if you were entirely free to plan your evening?

  8:00 – 9:00 PM ☐
  9:00 – 10:15 PM ☐
  10:15 – 12:30 AM ☐
  12:30 – 1:45 AM ☐
  1:45 – 3:00 AM ☐
  3:00 AM – 8:00 PM ☐

- If there is a specific time at which you have to get up in the morning, to what extent do you depend on being woken up by an alarm clock?

  Not all dependent ☐
  Slightly dependent ☐
  Fairly dependent ☐
  Very dependent ☐

- How easy do you find it to get up in the morning (when you are not woken up unexpectedly)?

  Not all easy ☐
  Not very easy ☐
  Fairly easy ☐
  Very easy ☐

- How alert do you feel during the first half-hour after you wake up in the morning?

  Not all alert ☐
  Slightly alert ☐
  Fairly alert ☐
  Very alert ☐

- How hungry do you feel during the first half hour after you wake up in the morning?

  Not all hungry ☐
  Slightly hungry ☐
  Fairly hungry ☐
  Very hungry ☐

- During the first half-hour after you wake up in the morning, how tired do you feel?

  Very tired ☐
  Fairly tired ☐
  Fairly refreshed ☐
  Very refreshed ☐

- If you have no commitments the next day, what time would you go to bed compared to your usual bedtime?

  Seldom or never later ☐
  Less than one hour later ☐
  1 – 2 hours later ☐
  More than two hours later ☐

- You have decided to engage in some physical exercise. A friend suggests that you do this for one hour twice a week and the best time for him is between 7:00 – 8:00 am. Bearing in mind nothing but your

own internal “clock”, how do you think you would perform?

Would be in good form	☐
Would be in reasonable form	☐
Would find it difficult	☐
Would find it very difficult	☐

- At what time of day do you feel you become tired as a result of need for sleep?

8:00 – 9:00 PM	☐
9:00 – 10:15 PM	☐
10:15 PM – 12:45 AM	☐
12:45 – 2:00 AM	☐
2:00 – 3:00 AM	☐

- You want to be at your peak performance for a test that you know is going to be mentally exhausting and will last for two hours. You are entirely free to plan your day. Considering only your own internal “clock”, which ONE of the four testing times would you choose?

8:00 AM – 10:00 AM	☐
11:00 AM – 1:00 PM	☐
3:00 PM – 5:00 PM	☐
7:00 PM – 9:00 PM	☐

- If you got into bed at 11:00 PM, how tired would you be?

Not at all tired	☐
A little tired	☐
Fairly tired	☐
Very tired	☐

- For some reason you have gone to bed several hours later than usual, but there is no need to get up at any particular time the next morning. Which ONE of the following are you most likely to do?

Will wake up at usual time, but will NOT fall back asleep	☐
Will wake up at usual time and will doze thereafter	☐
Will wake up at usual time but will fall asleep again	☐
Will NOT wake up until later than usual	☐

- One night you have to remain awake between 4:00 – 6:00 AM in order to carry out a night watch. You have no commitments the next day. Which ONE of the alternatives will suite you best?

Would NOT go to bed until watch was over	☐
Would take a nap before and sleep after	☐
Would take a good sleep before and nap after	☐
Would sleep only before watch	☐

- You have to do two hours of hard physical work. You are entirely free to plan your day and considering only your own internal “clock” which ONE of the following time would you choose?

8:00 AM – 10:00 AM	☐
11:00 AM – 1:00 PM	☐
3:00 PM – 5:00 PM	☐
7:00 PM – 9:00 PM	☐

- You have decided to engage in hard physical exercise. A friend suggests that you do this for one hour twice a week and the best time for him is between 10:00 – 11:00 PM. Bearing in mind nothing else but your own internal “clock” how well do you think you would perform?

Would be in good form	☐

Would be in reasonable form ☐
Would find it difficult ☐
Would find it very difficult ☐

- Suppose that you can choose your own work hours. Assume that you worked a FIVE hour day (including breaks) and that your job was interesting and paid by results). Which FIVE CONSECUTIVE HOURS would you select?

  5 hours starting between 4:00 AM and 8:00 AM ☐
  5 hours starting between 8:00 AM and 9:00 AM ☐
  5 hours starting between 9:00 AM and 2:00 PM ☐
  5 hours starting between 2:00 PM and 5:00 PM ☐
  5 hours starting between 5:00 PM and 4:00 AM ☐

- At what time of the day do you think that you reach your "feeling best" peak?

  5:00 – 8:00 AM ☐
  8:00 – 10:00 AM ☐
  10:00 AM – 5:00 PM ☐
  5:00 – 10:00 PM ☐
  10:00 PM – 5:00 AM ☐

- One hears about "morning" and "evening" types of people. Which ONE of these types do you consider yourself to be?

  Definitely a "morning" type ☐
  Rather more a "morning" than an "evening" type ☐
  Rather more an "evening" than a "morning" type ☐
  Definitely an "evening" type ☐

33 Do you have any other condition or injury not previously mentioned that the researchers should be aware of (i.e. that would prevent you from undertaking your normal duties)? ☐ No ☐ Yes

If YES, please elaborate

____

____

____

Thank you for taking the time to fill in this questionnaire

I believe the information I have provided to be true and correct.

SIGNED:____________________________________

DATE:__________________________

bushfire CRC **This project is funded by the Bushfire CRC**

CFS **The CFS is in full support of this research**

Appendix G: Pre- and post-testing injury and illness questionnaire

Pre-testing Questionnaire:

All participants:

Since you submitted your pre-participation medical questionnaire have you:

- Suffered an injury or illness? yes/no (please circle)
- Taken any form of medication in the last week? yes/no (please circle)

  If yes, what type of medication?____

  What was the dosage you took?____
- Experienced any recent muscle or joint pain (e.g. back pain, muscle cramps or stiffness etc)? yes/no (please circle)

  Remember: Please tell a researcher if you experience any twinges, pain or other discomfort whilst you're here.

Additional medical questions:

- Are you a smoker? yes/no (please circle)

If yes, approximately how many cigarettes do you smoke per day?_____________________________

What strength of cigarette do you smoke?____

Debrief or post-testing questionnaire:

Did you experience any twinges, pain of discomfort while you were here? yes/no (please circle)

If yes, on a scale of 1 to 10, how would you rate this pain?____

Do you think it affected your physical work during the testing period in anyway?__________________________

Female participants only:

Since you submitted your pre-participation medical questionnaire have you:

- Taken any form of medication (including oral contraceptives)? yes/no (please circle)

If yes, what type of medication?____

Do you know the name of your medication?____

What dosage did you take?

take?____

- When was your last period?____
- Do you typically experience any of the following symptoms associated with menstruation:

  cramps

  bloating

  tenderness

  other (please explain)

Appendix H: Peer-reviewed publication associated with Chapter 4

Chapter 4

The impact of temperature on the sleep characteristics of volunteer firefighters during a wildland fireground tour simulation

Cvirn MA [a], Smith BP [a], Jay SM [a], Vincent G [b], Ferguson SA [a]
[a] *Appleton Institute, Central Queensland University, Adelaide, South Australia*
[b] *Centre for Physical Activity and Nutrition Research, Deakin University, Burwood, Victoria, Australia*

Aims: *To investigate the effects of temperature on sleep during a simulated three-day wildland fireground deployment.* ***Methods:*** *Forty-nine volunteer firefighters (age range = 18-62 yrs; BMI = 27.4±4.4, 42 males, 7 females) participated in a three day, four night laboratory simulation of a wildland fireground deployment in either a control (n = 30) or heat condition (n = 19). The simulation included a baseline night and three experimental nights of 8 h sleep opportunities. Nighttime temperatures were set to 18-20°C on all four nights for the control condition and 23-25°C on the three experimental nights in the heat condition. Daytime temperatures were 23-25°C for the control condition and 33-35°C for the heat condition and participants performed repeated bouts of self-paced physical work activities based on wildfire suppression. Sleep was measured using ambulatory polysomnography and scored in accordance with the latest AASM criteria.* ***Results:*** *There was no significant main effect of condition, nor were there any interaction effects of condition by experimental night. However there was a significant main effect of experimental night ($p \leq 0.05$) on: minutes of Stage 1-3 and REM sleep, sleep onset latency (SOL) and wake after sleep onset (WASO); sleep efficiency; and total sleep time (TST). Results showed that stage 1 sleep decreased in the heat but remained constant in the control condition. Stage 2 sleep remained constant whilst minutes of Stage 3 and REM sleep increased in both conditions across experimental days. Finally, SOL and WASO initially decreased, whilst TST and sleep efficiency increased in both conditions over experimental nights 1 and 2 but were not significantly different from baseline levels on experimental night 3.* ***Discussion:*** *The effect of either thermoneutral or heated environmental temperatures on sleep physiology across a simulated three-day fireground deployment were similar, with the exception of stage 1 sleep decreasing in the heat. These results indicate that the sleep architecture of volunteer firefighters was not adversely affected by elevated day and night-time temperatures.*

Citation: Cvirn MA, Smith BP, Jay SM, Vincent G, Ferguson SA (2015). The impact of temperature on the sleep characteristics of volunteer firefighters during a wildland fireground tour simulation. In: Kennedy G, Sargent C (Eds). The Time of Your Life. Australasian Chronobiology Society, Melbourne, Australia, pp. 18-24.

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Australia is considered one of the most bushfire prone countries in the world with wildland fires increasing in both frequency and scale over the last decade [1]. This is believed to be associated with a global climactic shift towards hotter, drier summers [1]. Although robust data on rural firefighters' sleep patterns during campaigns remain sparse, reports suggest Australian firefighters experience a sleep curtailment of up to three to six hours per day during multi-day fire campaigns [1,6]. The increasing severity and frequency of wildland fires places an increased demand on rural fire agencies and personnel, often requiring extended work shifts of up to 12-15 h, with compromised rest between shifts [1]. Adding to the challenge, firefighters may be required to sleep in conditions of high ambient temperature. The impact of high temperature on sleep has not been measured in firefighters although there has been considerable research devoted to the impact of ambient temperature on sleep in laboratory studies [2].

Laboratory studies focusing on the effects of high or low ambient temperatures report that within a certain range of ambient temperatures referred to as the zone of 'thermoneutrality', sleep quality and quantity are maximal [2,5]. Although a thermoneutral zone is often discussed, a specific ambient temperature is rarely defined and tends to vary across studies [9]. However, most agree that in brief exposures (≤1 night), as ambient temperature increases, slow wave sleep (N3) and REM (R) sleep decrease [7,9,10,15]. During prolonged exposure to ambient temperatures, there is little evidence of a thermoregulatory sleep adaptation mechanism with only slight changes found in sleep architecture at low or high ambient temperatures for long durations [4,8,14]. Another paradox is that daytime and nighttime temperature manipulations appear to have opposite effects on N3 [2,4]. Daytime temperature manipulation studies have consistently shown that regardless of the method of heating (i.e., passive heating [13], temperature baths [11], or intense exercise [12]), the ensuing sleep episode will be marked by an increase in N3 with a simultaneous reduction in R sleep [11,12,13].

Whilst these studies reveal a number of findings important for the effects of day and night-time temperature manipulations on sleep architecture, they provide limited insight relating to the effects on sleep architecture for the conditions faced by wildland firefighters. This is because research designs, ambient temperatures, and participant samples are largely inconsistent with the environmental and occupational demands placed on firefighters and also their demographic profile. Presently, there is no objective polysomnography (PSG) measurements of firefighters sleep either in the field or the laboratory under any ambient temperature ranges (1,6). The purpose of the present study therefore, was to investigate the effect on firefighters' sleep quantity and quality during a simulated three-day four-night wildland fireground deployment conducted under either cool or hot, day- and night-time ambient temperature conditions.

Methods

Participants Participants were recruited from the Country Fire Service, Country Fire Authority, Tasmania Fire Service, NSW National Parks and Wildlife Service, and ACT Fire and Rescue. Firefighters participated in a wildland fireground deployment simulation and were assigned to one of two conditions. The control condition consisted of 30 participants (27 males (m), 3 females (f)) (M = 38.7 y, SD = 15.7 y) with a mean body mass index (BMI) of 27.5 kg/m² (SD = 4.8 kg/m²). The heat condition consisted of 19 participants (15 m, 4 f) (M = 34.9 y, SD = 12.7 y) with a BMI of 27.2 kg/m² (SD = 3.6 kg/m²). Ethics approval was obtained from the CQUniversity and Deakin University Human

Research Ethics Committees.

Procedure The simulated wildland fireground deployment consisted of three 24 h periods involving a baseline night with an 8 h sleep opportunity (time in bed [TIB] 22:30-06:30 h) followed by three experimental nights of 8 h sleep opportunities (TIB 22:00-06:00 h). For the control condition, day- and night-time temperatures remained between 18-20°C throughout the protocol. The baseline night was also consistent for both conditions with temperatures set between 18-20°C. From 11:30 h on experimental day one, temperature in the heat condition was 33-35°C during the day (06:00-18:00 h), and 23-25°C during the night (18:00-06:00 h) for the remaining experimental days. Temperature was maintained using reverse cycle air-conditioning, central thermostat heating, and additional portable heaters. Temperature was recorded by four climate nodes, and monitored continuously to ensure consistency.

Polysomnography and sleeping conditions Sleep was recorded using the Siesta Portable EEG system (Compumedics, Melbourne, Victoria, Australia). A standard montage of electrodes was applied; two channels of electroencephalography (EEG) (C4-M1, C3-M2); left and right electro-oculograms (ROC-LOC); and two channels of chin electromyography (EMG). Prior to bedtime, each participant had PSG Grass™ gold-cup electrodes (Astro-Med, Inc., West Warwick, RI) applied to their face and scalp. Participants slept in a single room (≤ five participants) and were provided with camping sleep stretchers, inflatable mattresses, and sleeping bags with accompanying pillows, cases and hygienic sleeping bags in-liners. All sleep records were blinded and analysed by a sleep technician in 30 s epochs in accordance with standard criteria [3].

Statistical analyses Linear mixed models were constructed specifying; total sleep time (TST) (min), sleep onset latency (min), light sleep (i.e., time spent in stage N1 or stage N2; min) deep sleep (i.e., time spent in stage N3 sleep; min), REM sleep (time spent in stage R sleep; min), wake after sleep onset time, WASO (min), sleep efficiency (i.e., total sleep/time in bed x 100; %); as dependent variables. Fixed effects of condition and experimental night (main and interaction) were specified with firefighter ID as a random effect. Post-hoc contrasts, least

Table 1. Results of linear mixed models analyses with condition and experimental night as fixed terms with participant ID as a random effect on measures of sleep quality and quantity.

	Condition			Experimental Night			Condition x Experimental Night		
Variable	**F**	**df**	**p**	**F**	**df**	**p**	**F**	**df**	**p**
N1 (min)	0.96	1, 47	.333	5.14	3,126	.002	0.84	3,126	.474
N2 (min)	1.50	1,47	.225	3.03	3,127	.032	0.54	3,127	.659
N3 (min)	0.051	1,46	.823	7.54	3,125	.000	1.01	3,125	.353
R (min)	1.65	1,44	.206	10.31	3,126	.000	1.30	3,126	.278
SOL(min)	0.01	1,46	.931	13.61	3,127	.000	0.25	3,127	.862
WASO(min)	0.73	1,45	.398	6.05	1,126	.001	0.34	3,126	.798
TST(min)	0.94	1,46	.338	11.43	3,126	.000	1.24	3,126	.299
Sleep efficiency (%)	0.32	1,46	.573	10.47	3,126	.000	0.18	3,126	.908

significant differences (LSD), were specified between levels of the fixed effect factor (condition and experimental night). Uncorrected degrees of freedom are reported.

Results

Higher ambient temperature was not associated with any differences in sleep architecture compared to thermoneutral conditions (Table 1). Changes were seen across days of the simulation (Table 1, Fig.1 and Fig. 2). Post-hoc tests revealed mins of N1 sleep in the control condition remained constant while in the heat condition N1 sleep was significantly reduced from baseline (BA) over experimental nights one and two (E1, E2) (Fig. 1). N2 sleep remained stable in both conditions over the duration of the experiment. N3 increased significantly in both conditions initially and remained different from baseline by E3 in the control condition. R sleep increased initially over E1 in the heat condition, then in both conditions over E2 and E3 (Fig. 1). Finally, SOL and WASO initially decreased, whilst TST and sleep efficiency increased in both conditions over E1 and E2 before returning to near BA levels by E3 (Fig. 2).

Discussion

The increasing amounts of N1 sleep revealed in the present study are in contrast to previous findings from brief (≤1 night) manipulations of ambient temperature, which produced decreases in the amount of N1 sleep at low or high temperatures [2,5,8]. However, the consistent amounts of N2 in the present study compliment earlier findings revealing that amounts of N2 sleep remain consistent during exposure to ambient temperature ranges of 18°C, 24°C, 29°C, 34°C, and 37°C [7]. The finding that N3 and R sleep increased in both conditions across experimental nights

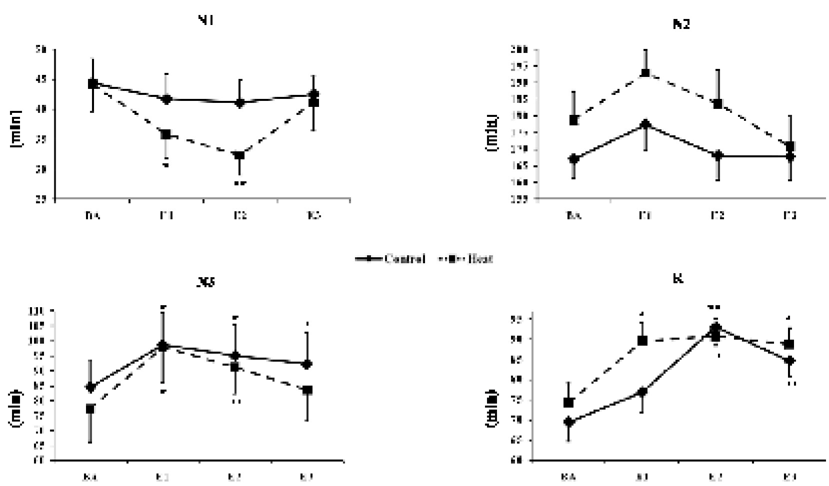

Figure 1. Sleep quantity. Comparison of mins of N1, N2, N3, and R between the conditions over baseline (BA), Experimental nights 1, 2 and 3 (E1, E2, & E3).*($p < .05$), ** ($p \leq .001$) indicates LSD post-hoc values were significantly different from BA. Values expressed as Mean ± SEM.

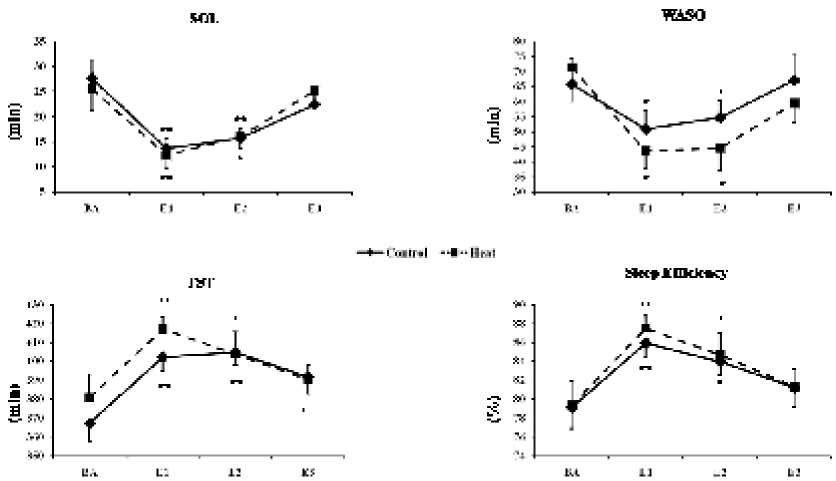

Figure 2. Sleep quality. Comparison of TST, SOL, WASO and Sleep Efficiency between the two conditions over BA, E1, E2 and E3.*($p \leq .05$), ** ($p \leq .001$) indicates LSD post-hoc values were significantly different from BA. Values expressed as Mean ± SEM.

appear to contrast a robust finding from earlier reports of brief exposure studies that as temperature increases, N3 and R sleep decrease [7,9,10,15]. However, it has also been found that provided with adequate bedtime clothing and covering, the microclimate established inside a bed will remain near constant at 29°C, whilst ambient temperature fluctuates from 16°C to 25°C [10]. This may also explain the results of the present study where participants were provided with adequate bedtime clothing and covering, hence the fluctuations in nighttime ambient temperatures from 18-20°C or 23-25°C might not have been sufficient to alter the microclimate inside the bedding. In addition, a zone of thermoneutrality may have been achieved, as research descriptively defines this as the range of temperature where TST, sleep efficiency, N3 and R sleep will be at their maximum whilst WASO and SOL will be reduced as seen in the present results, at least for lower ambient nighttime temperatures.

The increase in N3 over nights in both conditions is also consistent with previous research focusing on daytime temperature manipulations. A series of studies [11,12,13] demonstrated that a high and sustained body heating for one to two hours with an associated rapid rise in core boy temperature may trigger an increase in N3, regardless of the method of induction. This is consistent with the present findings as firefighters performed moderate bouts of self-paced physical activities during the day, which may have triggered a subsequent increase in N3 in the ensuing sleep episode in both conditions.

Finally, data from studies of more prolonged (> 1 night) exposures to high or low ambient temperatures suggest the existence of an adaptive mechanism(s)

protecting against sleep loss and modifications of sleep architecture [5,8,14]. The present results support not only the notion of a prolonged adaptation mechanism manifested as increasing N3 and R sleep, but also an initial adaptive mechanism in terms of increasing sleep quality, reflected in measures of SOL, WASO, TST, and sleep efficiency.

In conclusion, the present findings revealed that a simulated three day, four night wildland fireground deployment produced similar effects on sleep quality and quantity of firefighters in both cool and warm ambient day and night time temperatures. In addition, increased TST, sleep efficiency, N3 and R sleep and reduced SOL and WASO, may indicate that the terms of thermoneutrality were satisfied in both conditions, or they fell either side of quadratic curve of thermoneutrality [7], displaying similar deficits. Furthermore, the increases in N3 may be explained by an increased need for physical restitution [11,12,13] rather than as a sole effect of ambient temperature. Finally, the results of the present study suggest initial and potentially prolonged (> 1 day) adaptations in the sleep of firefighters during multi-day wildfire campaigns.

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Appendix I: Peer-reviewed publication associated with Chapter 5

Accident Analysis and Prevention 99 (2017) 389–394

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

The sleep architecture of Australian volunteer firefighters during a multi-day simulated wildfire suppression: Impact of sleep restriction and temperature

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ARTICLE INFO

Article history:
Received 26 June 2015
Received in revised form 23 October 2015
Accepted 6 November 2015
Available online 18 November 2015

Keywords:
Sleep restriction
Heat
Firefighter
Sleep architecture
Sleep quantity
Physical activity

ABSTRACT

Wildland firefighting exposes personnel to combinations of occupational and environmental stressors that include physical activity, heat and sleep restriction. However, the effects of these stressors on sleep have rarely been studied in the laboratory, and direct comparisons to field scenarios remain problematic. The aim of this study was to examine firefighters' sleep during a three-day, four-night simulated wildfire suppression that included sleep restriction and physical activity circuits representative of firefighting wildfire suppression tasks in varied temperatures. Sixty-one volunteer firefighters (37.5 ± 14.5 years of age, mean ± SD) were assigned to one of three conditions: *control* (n = 25; 8 h sleep opportunities and 18–20 °C), *awake* (n = 25; 4 h sleep opportunities and 18–20 °C) or *awake/hot* (n = 11; 4 h sleep opportunities and 33–35 °C during the day and 23–25 °C during the night). Results demonstrated that amounts of N1, N2 and R sleep, TST, SOL and WASO declined, whilst sleep efficiency increased significantly in the *awake* and *awake/hot* conditions compared to the *control* condition. Results also demonstrated that SWS sleep remained relatively stable in the *awake* and *awake/hot* conditions compared to *control* values. Most importantly, no significant differences were found for any of the sleep measures between the *awake* and *awake/hot* conditions. Thus, working in hot daytime temperatures in combination with sleep restriction during the night did not affect patterns of sleep compared to working in temperate conditions in combination with sleep restriction during the night. However, the effects on sleep of high (>25 °C) night-time temperatures with sleep restriction in addition to physical activity remains to be studied.

1. Introduction

Firefighting exposes personnel to combinations of occupational and environmental stressors including sleep restriction (Cater et al., 2007), long shifts of variable intensity physical activity (Cuddy et al., 2007; Phillips et al., 2012), and environmental extremes (Aisbett et al., 2012). Australian wild fires are known for hot temperatures (>45 °C) (Cheney, 1976), and require firefighters to work extended periods (up to 16 h per shift) (Cater et al., 2007; Phillips et al., 2012) in deployments that can last for days to weeks (Hunter and Authority, 2003; Rodriguez-Marroyo et al., 2012). As a result, cumulative sleep loss can occur, with firefighters reporting on average 3–6 h sleep per night during multi-day fire deployments (Cater et al., 2007; Gaskill and Ruby, 2004). Inadequate sleep has implications for performance and places individuals at increased risk of error and incident (Åkerstedt and Wright, 2009). Although data on Australian firefighters' sleep patterns are sparse, laboratory and military studies focusing on the individual and combined effects on sleep architecture of physical activity, sleep restriction and/or ambient temperatures provides some insight.

Laboratory studies on the effects of exercise on sleep reveal consistent increases in slow wave sleep (SWS) (Horne and Porter, 1975; Horne and Staff, 1983) and in some cases, associated reductions in rapid eye movement (REM) sleep (Horne and Moore, 1985) if exercise is conducted late in the afternoon and without a sufficient daytime recovery period. The effects of sleep restriction on sleep architecture are also well established, with declines in amounts of

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http://dx.doi.org/10.1016/j.aap.2015.11.013
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stage 1, 2, and REM sleep, and a conservation of SWS from sleep doses of 3–6 h per night for 7–14 consecutive days (Belenky et al., 2003; Van Dongen et al., 2003). However, the effects of varying ambient temperatures on sleep patterns are less clear.

Research using temperatures between 21 and 37 °C (Haskell et al., 1981) demonstrated that cold, rather than warm temperatures were generally more disruptive to sleep. Specifically, increases in stage 1 sleep and decreases in stage 2 and REM sleep were reported with 21 °C the most disruptive temperature. In contrast, no significant effects on the total duration of REM sleep or latency were reported during two consecutive nights sleep at temperatures of 13 °C, 16 °C, 19 °C, 22 °C, or 25 °C (Muzet et al., 1983). The effects on sleep during sleep restriction in cool and warm temperatures have also been examined.

Sleep restriction to 4 h for four nights at 20 or 35 °C was associated with decreased amounts of stage 1 sleep and wake after sleep onset (WASO) (Bach et al., 1994). Duration of stage 4 sleep increased over nights of sleep restriction at 20 °C but not 35 °C. Similar military research combining the effects of 4 h sleep restriction for 6 nights with an initial 90 h total sleep deprivation (TSD) period, during a tactical defence exercise in cold winter temperatures, revealed stage 2 sleep decreased whilst all other stages remained constant (Haslam, 1982).

Laboratory and field studies provide insight into the effects on sleep architecture of single or dual stressor combinations of physical activity, sleep restriction, and/or ambient temperatures however the combination of all three has not been studied in the laboratory. Further, where combinations of stressors (i.e., physical activity, sleep restriction and environmental extremes) are similar to that of firefighting, such as in military operations, direct comparisons are limited because such studies typically include periods of TSD at the beginning of experimental trials, in addition to limited control of extraneous variables such as fluctuations in natural weather conditions (Haslam, 1982; Lieberman et al., 2005). The aim of this study was to determine whether changes in sleep architecture from sleep restriction in combination with heat and physical activity are significantly different from those of sleep restriction and physical activity alone, and if these conditions differ from full sleep opportunities during a multi-day simulated wildfire suppression.

2. Methods

2.1. Participants

Participants were active volunteers recruited from the South Australian Country Fire Service, Country Fire Authority (Victoria), Tasmania Fire Service, New South Wales National Parks and Wildlife Service, and Australian Capital Territory Fire and Rescue. In groups of up to five, participants took part in a multi-day simulated wildfire suppression. Participants were assigned to one of three conditions. The *control* condition consisted of 25 participants (3 females (f)), 22 males (m) (mean = 36.7 y, SD = 15.9 y) with a mean BMI of 27.0 kg/m^2 (SD = 4.8 kg/m^2). The *awake* condition consisted of 25 participants (5 f, 20 m) (mean = 38.5 y, SD = 13.2 y) with a BMI of 29.2 kg/m^2 (SD = 4.9 kg/m^2). The *awake/hot* condition consisted of 11 participants (1 f, 10 m) (mean = 37.5 y, SD = 15.6 y) with a BMI of 26.7 kg/m^2 (SD = 4.6 kg/m^2). Power analyses indicated that a total sample size of 75 participants (across three groups) would be required ($\alpha = 0.05$, $1 - \beta = 0.80$), using an estimated effect size of $f = 0.16$ from previous research investigating changes in REM sleep and SWS with ambient temperature changes of 3 °C (Muzet et al., 1983, 1984). However, due to operational time constraints only 11/25 participants could be collected for the *awake/hot* group resulting in a total sample of 61 participants. This yielded an achieved study power of 0.71. Ethics approval was obtained from the CQUniversity and Deakin University Human Research Ethics Committees.

2.2. Procedure

The three-day, four-night multi-day simulated wildfire suppression consisted of a baseline night with an 8 h sleep opportunity (time in bed (TIB) 22:30–06:30 h), followed by two experimental nights with either 8 h or 4 h sleep opportunities (TIB 22:00–06:00 h or 02:00–06:00 h) for the *control* or *awake* and *awake/hot* conditions, respectively. The fourth night was a recovery sleep with all conditions provided with an 8 h sleep opportunity (TIB 22:00–06:00 h). For the *control* and *awake* conditions, day- and night-time temperatures remained between 18 and 20 °C throughout the protocol. From 11:30 h on experimental day one, temperature in the *awake/hot* condition was set to 33–35 °C during the day (06:00–18:00 h), and 23–25 °C during the two experimental nights and recovery (18:00–06:00 h). Temperature was monitored using a wireless temperature and humidity logger (HOBO ZW_003, One Temp Pty Ltd, Australia), data receiver (HOBO ZW_RCVR, One Temp Pty Ltd, Australia), and associated software (HOBO Pro Software, One Temp Pty Ltd, Australia). During the simulated dayshift firefighters performed physical-cognitive test circuits, three to five per day. Each 2 h circuit consisted of 55 min of physical work involving wildland firefighter suppression tasks (for a detailed methodology and the effects of sleep restriction on physical task performance the reader is referred to Vincent et al., 2015), 20–25 min of physiological testing (for a detailed methodology and the effects of heat on physiology and work performance the reader is referred to Larsen et al., 2015) and 20–25 min of cognitive testing (reported elsewhere), followed by a 15–20 min rest period.

2.3. Activity monitors

Actiwatch-64 (Mini-Mitter Philips Respironics, Bend, OR) or Actical Z-series (Mini-Mitter Philips Respironics, Inc.) devices were worn on the non-dominant wrist, prior to and during the experiment. Both activity monitors contain an omnidirectional piezoelectric accelerometer sampling movement at 32 Hz. Data collected with the Actical and Actiwatch (Mini Mitter Co., Inc., Bend, OR) correlated strongly with activity energy expenditure (AEE) and physical activity ratio (PAR) (Puyau et al., 2004) and the outputs from both accelerometers were also highly correlated ($r = 0.93$). As such, both activity monitors provide valid measures of AEE and PAR and can be used to discriminate sedentary, light, moderate and vigorous levels of physical activity.

2.4. Polysomnography and sleeping conditions

Sleep was recorded using the Siesta Portable electroencephalography (EEG) system (Compumedics, Melbourne, Victoria, Australia). A standard montage of electrodes was applied; two channels of EEG (C4-M1, C3-M2); left and right electro-oculograms (left outer canthus, right outer canthus); and two channels of chin electromyography. One and a half hours prior to bedtime each participant had polysomnography Grass™ gold-cup electrodes (Astro-Med, Inc., West Warwick, RI) applied to their face and scalp. All sleep records were blinded and analyzed by a sleep technician in 30 second epochs in accordance with standard criteria (Iber et al., 2007). Participants slept in individual beds located in a single room. Signals from each portable siesta transmitted wirelessly to designated participant laptops located in a separate room monitored overnight by a sleep technician. Ten minutes prior to scheduled bedtimes all sleep and monitoring equipment was placed in position and participants made themselves comfortable prior to lights

Table 1
Results of mixed-effect ANOVAs with physical activity (co-variate), condition and night as fixed terms and participant as a random effect on measures of sleep architecture and quantity.

	Physical activity			Condition			Night			Condition by night		
	F	*df*	*P*	*F*	*df*	*P*	*F*	*df*	*P*	*F*	*df*	*P*
N1 (min)	1.78	1150	.184	3.21	2.60	.047	12.42	3165	<.001	2.36	6157	.033
N2 (min)	1.56	1163	.213	15.19	2.60	<.001	80.38	3164	<.001	23.80	6155	<.001
N3 (min)	1.95	1211	.164	0.31	2.67	.732	10.96	3158	<.001	4.45	6152	<.001
R (min)	1.24	1142	.268	12.63	2.62	<.001	30.13	3166	<.001	14.39	6158	<.001
TST (h)	3.67	1128	.057	42.59	2.58	<.001	110.06	3165	<.001	40.75	6157	<.001
SOL (min)	4.48	1119	.036	4.39	2.60	.017	25.37	3168	<.001	2.04	6161	.064
WASO (min)	2.28	1176	.133	7.39	2.64	.001	25.19	3165	<.001	3.18	6157	.006
Efficiency (%)	1.78	1150	.184	3.21	2.60	.047	12.42	3165	<.001	2.36	6157	.033

out. Participants were provided with an electronic pager should they need assistance throughout the night and were awoken in the morning at the scheduled times with assistance from researchers to remove the monitoring equipment. For each sleep opportunity participants were provided with camping stretchers, inflatable mattresses, and sleeping bags with accompanying pillows and linen to simulate fireground conditions.

2.5. *Measures and statistical analyses*

Physical activity was measured by averaging the activity count for each 60 second epoch over the 16 h (06:00–22:00 h) period preceding each sleep episode. To assess differences in physical activity a preliminary mixed model analysis of variance was conducted with 2 fixed factors of condition (3 levels – *control*, *awake*, and *awake/hot*) and night (4 levels – baseline, experimental night 1, experimental night 2 and recovery) and a random factor of participants (n = 61). Results revealed significant differences in physical activity between conditions over nights (see Section 3.1). Since physical activity changed differentially across conditions, it was specified as a covariate in the models for sleep parameters. Models were run without, then with the covariate with optimal model fit for each sleep variable assessed by comparing Akaike weights between candidate models (Burnham and Anderson, 2002). The denominator degree freedoms for F statistics were computed using Satterthwaite approximation method.

For each sleep period, the following dependent variables were calculated: light sleep (i.e., time spent in stage N1 or stage N2 sleep; min), deep sleep (i.e., time spent in stage N3 sleep; min), REM sleep (time spent in stage R sleep; min), total sleep time (TST) (h), sleep onset latency (SOL) (min), WASO (min), and sleep efficiency (i.e., total sleep time/time in bed × 100; %). To assess the main effects of condition and night and the interaction effect of condition by night on sleep dependent variables, data were analyzed using a mixed model analysis of variance with 2 fixed factors of condition (3 levels) and night (4 levels) and a random factor of participants (n = 61) with physical activity as a co-variate. All statistical analyses were conducted using SPSS 20.0.

3. Results

3.1. *Physical activity*

Significant main effects on physical activity were found for condition ($F_{2,71}$ = 4.37, P < .05) and night ($F_{3,174}$ = 23.99, P < .001). There was also a significant interaction effect of condition by night on physical activity ($F_{6,174}$ = 2.76, P = .01). Post-hocs revealed significantly higher physical activity in the *awake* condition compared to the *control* and *awake/hot* conditions, on experimental day 2/experimental night 2 (P < .01 and P = .01, respectively) and experimental day 3/recovery night (P < .01 and P = .01, respectively).

3.2. *Sleep architecture and quantity*

Physical activity was not a significant covariate in any of the models and did not change the effects of the experimental manipulation on any sleep parameters with the exception of SOL (Table 1). There were significant main effects of condition on every sleep measure except N3 (Table 1). There were also significant main effects of night on all sleep measures, and interaction effects of condition by night for all sleep variables except SOL (Table 1). Fig. 1 shows sleep architecture/patterns for each of the stages of sleep in minutes. Stage N1 decreased significantly by experimental night 2, whilst N2 and R sleep significantly decreased over experimental nights 1 and 2, in both the *awake* and *awake/hot* conditions compared to the *control* condition (Fig. 1). N3 sleep remained relatively stable over nights in both the *awake* and *awake/hot* conditions with no significant differences compared to the *control* condition, except for on experimental night one between the *control* and *awake* conditions (Fig. 1).

Fig. 2 shows measures of sleep quantity. TST and WASO significantly decreased over experimental nights 1 and 2 in both the *awake* and *awake/hot* conditions compared to *control* and WASO was still significantly shorter by recovery in the *awake* condition compared to the *control* (Fig. 2). SOL was significantly shorter, whilst sleep efficiency was significantly longer, in the *awake* and *awake/hot* conditions compared to *control* by experimental night 2, and into recovery for SOL (Fig. 2).

4. Discussion

This study examined the effects on firefighters' sleep of a three-day four-night simulated wildfire suppression. The novel simulation involved sleep restriction or full sleep opportunities and physical activity in thermoneutral and hot temperatures. The findings suggest that there are no differences in sleep architecture or sleep quantity during a 4 h sleep opportunity in either slightly elevated or cool, thermoneutral day and night-time temperatures. There were however, significant differences between both sleep restriction conditions and the 8 h sleep opportunity in thermoneutral temperatures. That is, amounts of stages 1, 2 and REM sleep, TST, SOL and WASO declined, whilst efficiency was higher in the *control* condition compared to the *awake* and *awake/hot* conditions on the second night of sleep restriction. In addition, SWS sleep remained relatively stable over the two consecutive nights of sleep restriction and recovery in the *awake* and *awake/hot* conditions compared to *control* values. The only exception was reduced SWS in the *awake* condition on the first sleep restriction night compared to the *control* condition. These results are consistent with previous seminal studies on chronic sleep restriction demonstrating SWS is relatively conserved whilst stage 1, 2 and REM sleep decline relative to the amount of sleep restriction (Belenky et al., 2003; Van Dongen et al., 2003).

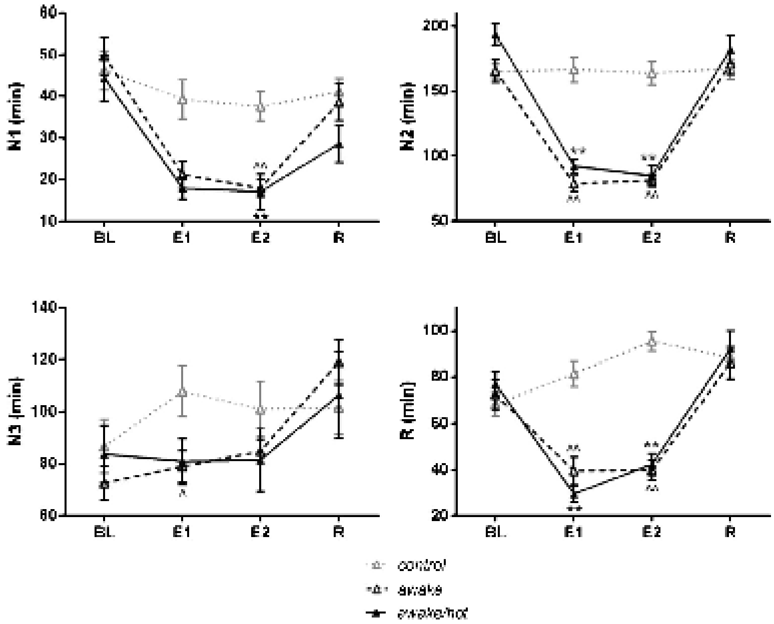

Fig. 1. Sleep architecture. Comparison of sleep stages N1, N2, N3, and R between the three conditions over Baseline (BL), Experimental nights 1 and 2 (E1, E2) and Recovery (R).**($P < .01$) indicates *control* condition values were significantly different from *awake/hot* condition.^($P < .05$),^^($P < .01$) indicates *control* condition values were significantly different from *awake* condition. Values expressed as mean ± standard error of the mean (SEM). Error bars represent SEM.

In the current study, performing physical work in high 33–35 °C daytime temperatures did not impact on sleep beyond the effects of sleep restriction alone. This was surprising given a series of studies reporting that high and sustained body heating for 1–2 hours in the afternoon may trigger an increase in SWS regardless of the method of induction (i.e., passive heating (Horne and Staff, 1983), warm temperature baths (Horne and Reid, 1985), or intense exercise (Horne and Porter, 1975)). Similarly, the finding that SWS (stage 3 and stage 4 sleep combined) remained stable during sleep restriction at 18–20 °C contrasts the results of a previous sleep restriction study (Bach et al., 1994) showing that sleep restriction to 4 h for four consecutive nights in 20 °C was associated with a significant increase in stage 4 sleep compared to full 8 h rest opportunities.

Similarly, it would appear that sleep restriction in mild, slightly elevated night-time compared to thermoneutral night-time temperatures, does not adversely affect sleep architecture and quantity. This result is consistent with our previous study reporting no significant differences in sleep patterns between warm (33–35 °C) and thermoneutral (18–20 °C) temperatures with 8 h rest opportunities (Cvirn et al., 2015). Consistent with previous research no significant changes in sleep stages, with the exception of stage 2, have been demonstrated for five consecutive nights sleep at 21 °C compared with five nights at a thermoneutral temperature of 29 °C (Palca et al., 1986). Similarly, no differences in amounts of REM sleep were reported from two nights sleep at temperatures of 13 °C, 16 °C, 19 °C, 22 °C, or 25 °C (Muzet et al., 1983).

However these findings contrast research (Haskell et al., 1981) showing that cold temperatures (defined as 21 °C and 24 °C) were associated with increased amounts of stage 1 sleep, WASO and reduced amounts of stage 2 and REM sleep, compared to a thermoneutral (29 °C) temperature. Although in the present study reduced amounts of stage 2 and REM sleep were seen in both the *awake* and *awake/hot* conditions, the two temperature conditions did not significantly differ in relation to stage 2 or REM sleep. The decrease is therefore more likely due to sleep restriction rather than the experimental temperature manipulation. It should be noted however, that in protocols such as this one and Muzet et al. (1983) where bedding (i.e., sheets and blanket) is provided, the thermoneutral temperature is approximately 19 °C (18–20 °C). However, if participants are required to sleep semi-naked (i.e., shorts; Haskell et al. (1981) and Palca et al. (1986)) the thermoneutral temperature may be higher, around 29 °C. This is due to the finding with adequate bedtime clothing and covering, the microclimate inside a bed will remain near constant at 29 °C, while ambient temperature can be as low as 16 °C (Muzet et al., 1984).

It is possible that night-time temperatures in the range of 18–20 °C or 23–25 °C are too mild to affect night-time sleep. The suggestion that elevated night-time temperatures may be more disruptive to sleep is also consistent with previous research showing increases in WASO and decreases in SWS sleep following ambient temperature increases from 26 °C to 32 °C during the second half of the sleep (Okamoto-Mizuno et al., 2005). Similarly, lower amounts of stage 1 and REM sleep, SWS and TST with increased number and duration of awakenings have been reported with the use of high electric blanket temperatures during the night (Karacan et al., 1978).

Uneven participant numbers between conditions may have contributed to the pre-existing differences at baseline, where significantly increased SOL in the *awake* condition resulted in significantly decreased TST, compared to the *awake/*hot and *control* conditions. This might also explain why there were no significant pre-existing differences on the baseline night for any sleep measures between the *awake* and *control* conditions where participant numbers were

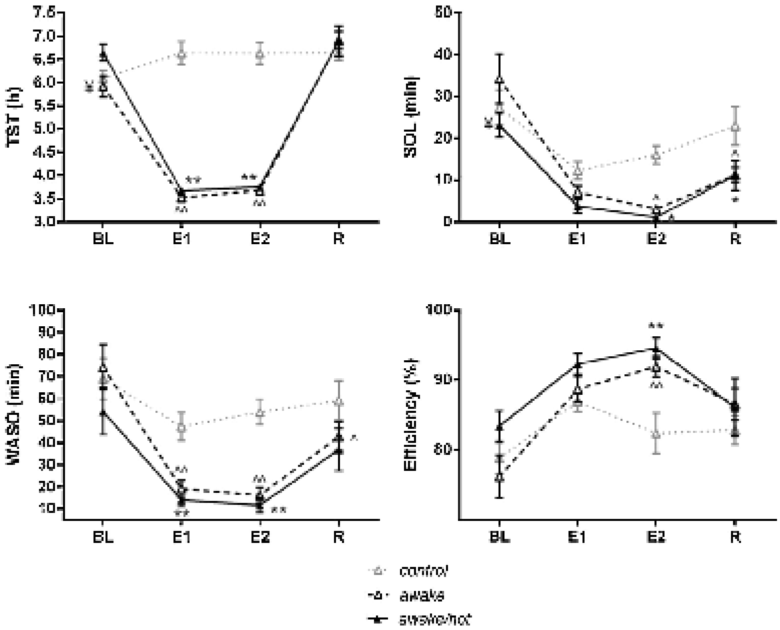

Fig. 2. Sleep quantity. Comparison of TST, SOL, WASO and Efficiency between the three conditions over BL, E1, E2 and R. *($P < .05$), **($P < .01$), indicates *control* condition values were significantly different from *awake* condition. ^($P < .05$), ^^($P < .01$), indicates *control* condition values were significantly different from *awake/hot* condition. ∀ indicates *awake* condition values were significantly different from the *awake/hot* condition ($P < .05$). Values expressed as mean ± SEM.

even. Also as the study was slightly underpowered the findings of no differences between the sleep restriction temperature conditions should be interpreted carefully due to lower participant numbers in the *awake/hot* condition. Additionally, physical activity was a significant covariate for SOL and was associated with a significant decrease in SOL on the second night of sleep restriction and recovery for the *awake* and *awake/hot* conditions compared to *control* values. However, preliminary analyses revealed only the *awake* condition, not the *awake/hot* condition was significantly higher in physical activity compared to the *control* condition over these nights. Hence, the potential for an inverse relationship to exist with increases in physical activity associated with decreases in SOL cannot be substantiated by our findings. However, such an inverse relationship has been reported in a previous meta-analysis on the effects of acute and chronic exercise on sleep (Kubitz et al., 1996).

This study provides the first investigation into the sleep architecture of wildland firefighters during sleep restriction and elevated temperatures. The findings indicate that the effect of sleep restriction is more detrimental to firefighters' sleep than heat. The effect of higher ambient temperatures at night remains to be studied given the increase in this study was mild from 18–20 °C to 23–25 °C. Future research is needed to consider the impact of high night-time ambient temperatures (>25 °C) on sleep architecture in combination with other stressors such as daytime physical activity and sleep restriction.

Acknowledgements

The authors would like to thank the rural firefighting agencies for their participation and recruiting volunteers for the study including the Country Fire Authority (CFA), Tasmania Fire Service, New South Wales Fire Service, Country Fire Service (CFS) and Australian Capital Territory Fire Service. We also thank the staff and students from Central Queensland University (Appleton Institute), and the School of Exercise and Nutrition Sciences at Deakin University. The project was funded by the Bushfire Cooperative Research Centre.

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